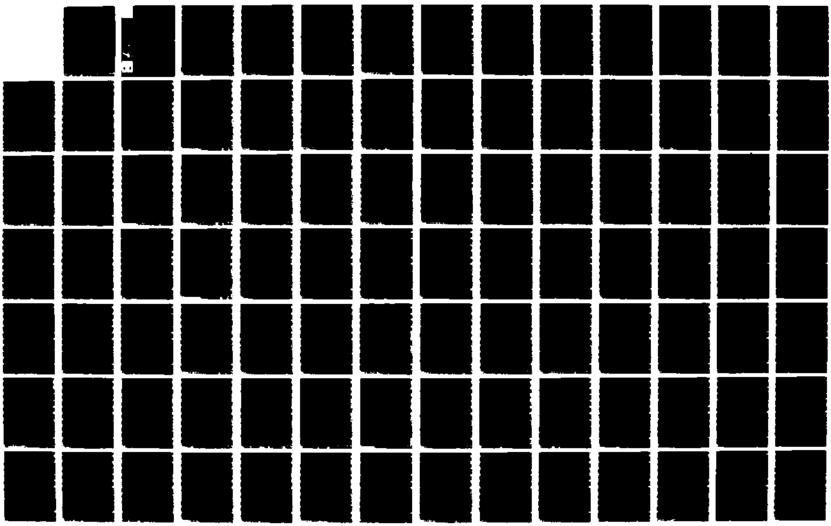
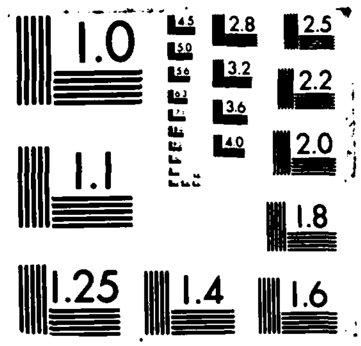
AD-A181 372 ENVIRONMENTAL & WATER QUALITY OPERATIONAL STUDIES: IMPROVEMENT OF HYDROPO (U) ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MS ENVIR 1/2

UNCLASSIFIED S C WILHELMS ET AL MAR 87 WES/TR/E-87-3 F/G 10/2 NL




1.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6

US Army Corps
of Engineers

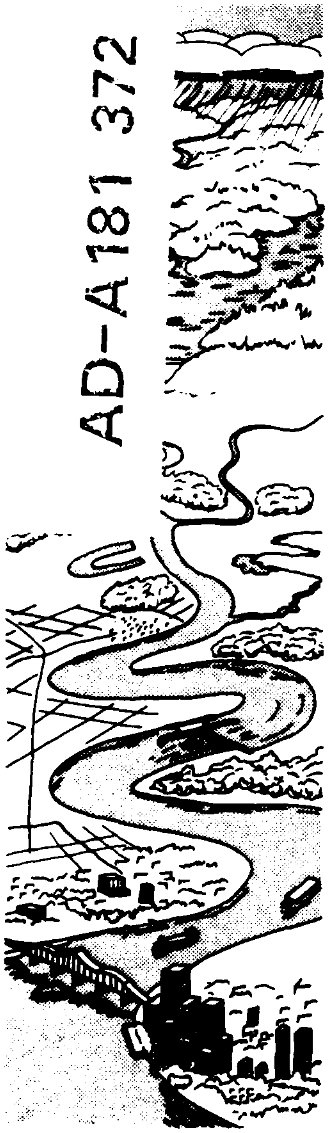
DTIC FILE COPY

(12)

ENVIRONMENTAL & WATER QUALITY
OPERATIONAL STUDIES

TECHNICAL REPORT E-87-3

AD-A181 372



IMPROVEMENT OF HYDROPOWER RELEASE DISSOLVED OXYGEN WITH TURBINE VENTING

by

Steven C. Wilhelms, Michael L. Schneider,
Stacy E. Howington

Hydraulics Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
PO Box 631, Vicksburg, Mississippi 39180-0631

March 1987

Final Report

Approved For Public Release; Distribution Unlimited

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

Under CWIS Work Unit 31604
(EWQOS Work Unit VIIIA.3)

Monitored by Environmental Laboratory
US Army Engineer Waterways Experiment Station
PO Box 631, Vicksburg, Mississippi 39180-0631

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188
Exp Date Jun 30, 1986

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS A181372
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) Technical Report E-87-3
6a. NAME OF PERFORMING ORGANIZATION USAEWES Hydraulics Laboratory 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION USAEWES Environmental Laboratory
6c. ADDRESS (City, State, and ZIP Code) PO Box 631 Vicksburg, MS 39180-0631	7b. ADDRESS (City, State, and ZIP Code) PO Box 631 Vicksburg, MS 39180-0631
8a. NAME OF FUNDING/SPONSORING ORGANIZATION US Army Corps of Engineers 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) Washington, DC 20314-1000	10. SOURCE OF FUNDING NUMBERS See reverse PROGRAM ELEMENT NO. / PROJECT NO / TASK NO. / WORK UNIT ACCESSION NO

11. TITLE (Include Security Classification)

Improvement of Hydropower Release Dissolved Oxygen with Turbine Venting

12. PERSONAL AUTHOR(S)

Wilhelms, Steven C., Schneider, Michael L., and Howington, Stacy E.

13a. TYPE OF REPORT	13b. TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final report	FROM ____ TO ____	March 1987	106

16. SUPPLEMENTARY NOTATION

Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Dissolved oxygen; Hydropower; Oxygenation; Reaeration; Turbine venting

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report summarizes the various in-lake, in-structure, and downstream techniques to enhance the dissolved oxygen concentration of hydropower releases. In-lake and in-structure techniques appear to be the most applicable for Corps of Engineers projects because of the large discharges of most hydropower projects. Of these, the in-structure techniques, particularly turbine venting, appear very attractive considering cost and degree of improvement. Tests were conducted at the Clarks Hill Dam powerhouse to evaluate various aspects of turbine venting and thereby provide a data base to develop predictive and design capabilities for turbine venting systems. Results of these tests indicated that, at most, the oxygen deficit in the penstock could be reduced by about 30 percent. That is, if the penstock oxygen deficit is 8.0 mg/ℓ, then, at most, about 2.4 mg/ℓ of oxygen could be absorbed into the release flow. Two reaeration processes that contributed to the overall oxygen transfer were observed in the tests: (a) due to the turbulence in the tailrace area

(Continued)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b TELEPHONE (Include Area Code) / 22c OFFICE SYMBOL

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE

Unclassified

10. WORK UNIT

EWQOS Work Unit VIIIA.3 (CWIS No. 31604)

19. ABSTRACT (Continued).

and (b) due to the air bubbles (vented through the turbine) as they traveled through the draft tube. A numerical computer model ~~of these~~ processes was developed that included the impact of the changes in thermodynamic (pressure) state as the bubbles passed through the draft tube. By developing this "pressure-time history," the increased potential for oxygen transfer due to the increase in hydrostatic pressure was included in model formulation. Good agreement was obtained in comparing model predictions and oxygen uptake data from previous tests at Clarks Hill. An example of model application and economic analysis is presented. The entire process analysis and resulting numerical model are based on the data collected at Clarks Hill. Thus, application to similarly sized and designed projects should produce acceptable results. However, caution should be exercised for application to other type turbines, low-head, or small projects.

PREFACE

This investigation was conducted by the US Army Engineer Waterways Experiment Station (WES), Hydraulics Laboratory (HL), under the direction of Messrs. F. A. Herrmann, Jr., Chief of the HL; H. B. Simmons, former Chief of the HL; and J. L. Grace, Jr., Chief of the Hydraulic Structures Division. The effort was supported by the Environmental and Water Quality Operational Studies (EWQOS) Program, Work Unit VIIIA.3 (CWIS No. 31604), entitled "Evaluate Alternatives for Aeration/Oxygenation of Hydropower Releases." The EWQOS Program is sponsored by the Office, Chief of Engineers (OCE), US Army, and is assigned to the Environmental Laboratory (EL), WES. The OCE Technical Monitors were Mr. Earl Eiker, Dr. John Bushman, and Mr. James L. Gottesman. Dr. J. L. Mahloch, EL, was the WES Program Manager of EWQOS.

The study was conducted under the direct supervision of Mr. Jeffery P. Holland, Chief of the Reservoir Water Quality Branch (RWQB); Dr. Dennis R. Smith, former Chief of the RWQB; and with the coordination of the US Army Engineer District (USAED), Savannah, and the Tennessee Valley Authority. Messrs. Steven C. Wilhelms, Michael L. Schneider, and Stacy E. Howington prepared this report. Assisting in the testing were the authors as well as Messrs. Holland, Charles H. Tate, Jr., Hubert R. Smith, and the Clarks Hill Reservoir personnel. Messrs. Gary Mauldin and James Gallagher, USAED, Savannah, provided guidance, technical assistance, and support during the field studies. The report was edited by Ms. Jessica S. Ruff of the WES Information Products Division.

COL Allen F. Grum, USA, was the previous Director of WES. COL Dwayne G. Lee, CE, is the present Commander and Director. Dr. Robert W. Whalin is Technical Director.

This report should be cited as follows:

Wilhelms, S. C., Schneider, M. L., and Howington, S. E. 1987. "Improvement of Hydropower Release Dissolved Oxygen with Turbine Venting," Technical Report E-87-3, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
feet	0.3048	metres
foot-pounds per pound (force/mass ratio)	9.806650	newtons per kilogram
foot-pounds (force) per second	1.355818	watts
horsepower (550 foot-pounds (force) per second)	745.6999	watts
inches	2.54	centimetres
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (force) per square inch	6.894757	kilopascals
pounds (force) per square foot	47.88026	pascals
square feet	0.09290304	square metres

IMPROVEMENT OF HYDROPOWER RELEASE DISSOLVED OXYGEN WITH TURBINE VENTING

PART I: INTRODUCTION

Background

1. Hydroelectric power generation has proven to be one of the most attractive energy sources available. Past energy shortages have spurred growth in the number of hydroelectric facilities, and numerous existing and proposed sites for hydropower projects are being evaluated and developed. Hydropower is presently meeting about 12 percent of our nation's energy needs. Additionally, several thousand potential hydropower sites have been identified, and the attractive attributes of hydropower have resulted in evaluation, design, or construction of hydropower facilities for many of these sites.

2. From the standpoint of energy resource conservation, hydropower is very attractive because the energy source (water held in the reservoir) is renewable. Hydropower is also flexible from an operational standpoint. Changes in power demand due to daily peaking and seasonal fluctuation dictate the need for a rapidly responding energy source. Hydropower generation can usually be stopped, started, or changed in a matter of minutes by simply controlling the flow rate of water through the turbine. This provides nearly optimum compatibility with peaking demand. If the supply of water is abundant, hydropower can also be operated continuously to meet baseload power demand.

3. Hydropower is considered one of the cleanest major sources of electrical energy. However, adverse environmental impacts resulting from a proposed or modified hydropower project must be evaluated and techniques that minimize or mitigate damage to the environment must be developed.

Problems and Concerns

4. A frequently cited problem associated with a proposed or existing hydropower project is the release of water with a low dissolved oxygen (DO) concentration. This problem is typically the result of low-level releases from a density-stratified pool coupled with an in-lake oxygen demand. Due to the heating of surface waters, a reservoir stratifies such that a surface layer of warm water, the epilimnion, resides above a layer of cooler water, the hypolimnion. DO concentrations in the epilimnion are generally high due to the extensive transfer of oxygen at the air/water interface. The hypolimnion, may however, become oxygen deficient. The presence of density stratification acts to inhibit vertical mixing, thereby limiting the transfer of oxygen into the hypolimnion. When a hypolimnetic oxygen demand is coupled with this absence of oxygen replenishment, deterioration of hypolimnetic water quality, often to the point of anoxia, occurs.

5. Several problems may develop under anoxic conditions, such as the dissolution of trace metals, release of nutrients, formation of hydrogen sulfide, and depression of pH. Hydropower intakes are often located in the hypolimnion, resulting in poor water quality releases downstream during power generation. Depending upon the severity of the DO deficiency in the release, it may be necessary to employ one or more techniques to enhance DO concentration in hydropower releases.

6. The retrofit of an existing flood control or other nonpower project with hydropower has produced a number of water quality concerns (Wilhelms 1983). At many nonpower projects, significant reaeration (Wilhelms and Smith 1981) (often to near saturation) occurs in the high-velocity regions of open-channel flow through the outlet works and stilling basin. The incorporation of a downstream turbine and pressurized conduit results in the loss of this reaeration. While the impacts of this loss of reaeration are often site-specific, a change in release quality from highly oxygenated to near-anoxia (as described in paragraphs 4 and 5) would severely impact the downstream environment.

7. A number of Corp of Engineers (CE) projects have been designed

with multilevel intakes in order to withdraw water from different levels in a stratified reservoir. This provides a means of releasing water with various temperatures, DO concentrations, and levels of suspended sediments. The addition of downstream flow control resulting from hydropower retrofitting may limit or negate this capability. Many potential concerns regarding water quality have been encountered and identified at existing, proposed, or add-on hydropower projects. Based on these problems, guidance is needed for the design and operation of hydropower reaeration techniques to enhance release water quality.

Study Objectives and Scope

8. A wide variety of techniques are available to improve the DO of water released from hydropower projects. The system most effective at a specific hydropower site will depend upon many factors, including the degree of DO enhancement required, rate of release, turbine type and operation, upstream and downstream water quality objectives, and availability of economic resources. Selection of the "best" system must involve weighing the costs and benefits of each technique with regard to site-specific concerns. The initial objective of this study was to investigate means of enhancing hydropower releases. This investigation led to extended evaluation of one technique, turbine venting, in terms of dissolved gas uptake and the costs incurred by altering turbine operating characteristics. The results of this study should provide general guidance for the applicability of turbine venting to projects similar to the study site at Clarks Hill Reservior, Georgia. However, caution should be exercised in application to other type turbines, low-head, or small projects. As a backdrop to the documentation on turbine venting, an overview of techniques for improving reservoir releases is presented.

PART II: POTENTIAL TECHNIQUES FOR RELEASE ENHANCEMENT

9. As mentioned, the most frequently cited adverse impact for proposed or existing hydropower projects is the release of water with a relatively low DO content. A wide range of techniques are available to address the problem of low DO concentrations in project releases. These potential solutions vary greatly in terms of economic impact, operational complexity, and degree of influence. The following discussion outlines the many techniques which have been identified to improve DO releases from reservoirs and lakes. Additional details on many of these techniques were presented by Bohac et al. (1983).

10. Techniques to improve hydropower releases may be grouped into three general areas: forebay, tailwater, and in-structure systems. Examples of techniques in each area are:

- a. Forebay systems.
  - (1) Hypolimnetic aeration/oxygenation.
  - (2) Artificial destratification.
  - (3) Localized mixing/local destratification.
  - (4) Selective withdrawal.
- b. Tailwater systems.
  - (1) Diffused air aeration.
  - (2) Weirs or channel steps.
  - (3) Surface aeration.
  - (4) Molecular oxygen injection.
  - (5) Miscellaneous methods.
- c. In-structure systems.
  - (1) Air aspiration.
  - (2) Air or oxygen injection.

Techniques in each of these areas will be discussed in the following sections.

Forebay Systems

Hypolimnetic aeration/oxygenation

11. Many forebay systems improve release DO concentrations by simply increasing the DO concentration of water in the forebay area. One such method, commonly termed hypolimnetic aeration (or oxygenation), involves injecting air into the hypolimnion. The purpose of hypolimnetic aeration is to increase the DO concentrations of hypolimnetic waters while maintaining the existing thermal stratification.

12. Three major categories of hypolimnetic aeration have been suggested by Fast and Lorenzen (1976): mechanical aeration, air injection, and oxygen injection. Mechanical aeration has proven to be the most efficient means of hypolimnetic aeration for shallow lakes. This method transports water to the surface where it is mechanically agitated and returned to the hypolimnion. Air injection systems mix hypolimnetic and epilimnetic water with an aerator and then return the enhanced waters to the hypolimnion. Air injection aerators have demonstrated the highest oxygen transfer efficiencies per unit energy expended in pumping. Oxygen injection systems represent the third class of hypolimnetic aeration. In this operation, molecular oxygen is injected into the hypolimnion instead of air. The design and operation of hypolimnetic oxygenation systems are discussed in Holland and Tate (1984).

13. The benefits of maintaining the thermal characteristics of a reservoir while aerating hypolimnetic waters include: (a) increasing the pH of hypolimnetic water by lowering concentrations of iron, manganese, and hydrogen sulfide; (b) preventing anoxic conditions which are potentially hazardous to fish; (c) maintaining coldwater (hypolimnetic) resources; and (d) maintaining heterogeneous resources of water quality within the reservoir which can be used by selective withdrawal techniques to meet downstream water quality objectives.

14. When used in conjunction with hydropower projects, hypolimnetic aeration does not decrease the efficiency of turbines (Speece et al. 1977, Merritt and Leggitt 1981). A major drawback of air/oxygen injection in the hypolimnion is that the volume of water requiring

enhancement, in most cases, necessitates a large aeration/oxygenation system (Speece 1975a). If oxygen, rather than air, is required for injection, the costs of oxygen purchase, transport, and storage may be quite high (Speece 1975b). Hypolimnetic aeration may also result in nitrogen supersaturation, which can be hazardous to fish surfacing downstream of the project.

Artificial destratification

15. Artificial destratification is another alternative that can be used to enhance in-reservoir and release water quality (Dortch 1979, Dortch and Holland 1980, Fast and Hulquist 1982, Holland and Dortch 1984). Destratification requires the addition of sufficient energy to a reservoir to overcome the buoyant forces associated with density stratification and thereby remove the inhibition to reservoir circulation. Total reservoir circulation enables the transport of oxygen from the atmosphere throughout the reservoir by convection and diffusion.

16. Two methods of artificially destratifying a lake or reservoir are: mechanically pumping water (hydraulic) and bubbling air (pneumatic). The hydraulic method jets water from one region (hypolimnion) of the reservoir into another region (epilimnion). Pneumatic destratification results from mixing caused by an air/water plume as it rises from the bottom to the surface. Although pneumatic destratification has been more widely applied, laboratory tests have indicated that hydraulic destratification is possibly more efficient than pneumatic mixing (Dortch 1979).

17. A detrimental effect of destratification, however, is that it results in the loss of coldwater resources that may be of concern to reservoir fisheries and a project's ability to meet release coldwater temperature objectives. The redistribution of thermal energy may have the effect of increasing the total heat content of the reservoir. The redistribution of nutrients common to the hypolimnion throughout the water column may result in changes to the biological and chemical properties of a reservoir. More details are provided in Pastorok, Lorenzen, and Ginn (1982).

Localized mixing/
local destratification

18. Localized mixing systems are designed to destratify the reservoir in the vicinity of the outlet as opposed to total reservoir destratification (Garton and Rice 1974, Garton and Jarrell 1976, Dortch and Wilhelms 1978, and Holland 1984). A downward vertical jet of epilimnetic water transports better quality water into the withdrawal zone of the outlet in the hypolimnion. A portion of the transported epilimnetic water will then be withdrawn from the reservoir along with a quantity of hypolimnetic water, thus diluting the hypolimnetic outflow and improving release quality. The jet of water from the epilimnion may be generated by a number of techniques, ranging from an axial flow propeller to a surface pump. This technique is generally suited for smaller flow rates since a practical limit of epilimnetic pumping exists which would generally provide little quality enhancement for large-volume hydropower releases. One drawback of localized mixing is accidental total lake destratification. A second is the likely warming of release waters due to the increased epilimnetic contribution to the flow.

19. Local destratification using a rising bubble plume has been employed as an alternative to localized mixing described in the previous paragraph (US Army Engineer District (USAED), Savannah 1969; Tennessee Valley Authority (TVA) 1984). The objective of this system is to create sufficient mixing locally such that the water in the immediate vicinity of the outlet is destratified, resulting in improved release water quality. The disadvantages of the local destratification system are similar to those for localized mixing.

Selective withdrawal

20. The addition of selective withdrawal capabilities to a hydropower project is another alternative that can potentially improve the quality of release water. Selective withdrawal (Wilhelms 1985) implements the concept of withdrawing water from different levels in a stratified reservoir to achieve a desired release characteristic. For example, if warm releases are desired, surface withdrawal would be in

order. If cold water is desired for release, a low-level outlet would be operated to withdraw bottom water.

21. A separate structure may be added to the project (Maynord and Tate 1983), or facilities (or structural modifications) may be added to the existing structure (George, Dortch, and Tate 1980) to provide control of or modify the outlet elevation through which release water is withdrawn. Multilevel withdrawal provides the capability to release water from two elevations in the pool. Thus, control of release quality can be achieved. It must be noted, however, that conflicting objectives may occur if cold water with high DO is desired. Usually, only surface water is high in DO. Therefore, withdrawal of surface water to improve DO would also increase the temperature of release water, resulting in a potential conflict with a coldwater temperature objective.

Tailwater Systems

Diffused-air aeration

22. One method of improving the DO of the water in the tailrace is by diffused-air aeration. In this technique, air is injected into the flowing water via horizontal pipes, hoses, or mats in such a manner that significant air-to-water contact is achieved. This allows the greatest efficiency of oxygen absorption from rising air bubbles into the surrounding water. The effectiveness of such systems depends upon the ability to inject sufficient air relative to the water flow rate.

Weirs or channel steps

23. Significant oxygen uptake may occur in river reaches containing overfall weirs or multistage channel steps. Oxygen transfer occurs both from molecular diffusion and turbulent mass transfer. The major factor in determining the amount of reaeration at these river features is the fall head (Gameson 1957). Additionally, the efficiency of reaeration through these structures is highly dependent on the depth of flow. Thus, for the very high flows which are characteristic of most hydropower projects, the oxygen transfer would be limited. Further, since the height of fall determines the amount of reaeration, the

addition of this type structure to an existing project would cause a significant loss in the head available for power production.

Surface aeration

24. Surface aerators have been used only to a limited extent for improving tailwater quality. This alternative usually involves spraying a portion of the water up into the air while agitating and mixing the surface waters. The efficiency of this method depends upon the degree of atmospheric exposure of the body of water and increases with greater surface flow velocities. Surface aerators suffer from the following drawbacks: (a) aesthetically unattractive and noisy, (b) navigation restrictions, and (c) limited effectiveness for large volumes or flows.

Molecular oxygen injection

25. The use of molecular oxygen has been proposed as an alternative method of tailwater aeration. Oxygen concentration in oxygen gas is about five times that of air, which leads to a higher uptake efficiency. It has been proposed that fine nozzles or diffuser mats be used to generate the oxygen bubble plume. The microbubbles enhance oxygen absorption because of the large water/bubble interfacial area. The major problem with using molecular oxygen is the cost of manufacturing or purchasing, transport, and storage.

Miscellaneous methods

26. Miscellaneous aeration methods include Venturi nozzles, shaft aerators, spray cones, and various surface and submerged aerators (Bohac et al. 1983). Most of these methods were developed for use at cooling-water and sewage-effluent outlets. These situations have small flow rates compared to most hydropower facilities and thus have limited applicability downstream of most CE projects.

In-Structure Systems

Air aspiration systems

27. Aspiration systems take advantage of the hydrodynamic/hydraulic properties of the turbine which create low-pressure regions downstream of the turbine blades. These subatmospheric pressures, when

vented to the atmosphere, cause air to be drawn into the water flow. The existence and magnitude of a subatmospheric pressure in the draft tube are dependent upon the operating conditions, the flow rate, geometric properties of the turbine and draft tube, and headwater and tailwater elevations. The air flow rate into the water flow is a function of the pressure differential between the atmosphere and the draft tube and the losses in the aeration supply line.

28. Francis turbines, the type used at many CE projects, are usually vented to the atmosphere (Figure 1) during low-flow operations to alleviate negative pressures that promote cavitation. Venting under these operating conditions also makes the turbine run more efficiently. The automatic venting system (cam-operated valve) that allows air to be drawn into the draft tube is called the "vacuum-breaker" system. Usually, the vacuum-breaker system operates over the lower half of the range of turbine discharges. The cam action closes the vacuum-breaker valve at about a 50-percent opening on the control gates. Even by overriding the automatic closure of the vacuum-breaker valve and holding the valve open, air aspiration is not extended significantly into the higher turbine discharges because negative gage (subatmospheric) pressures in the draft tube may not exist at higher discharges.

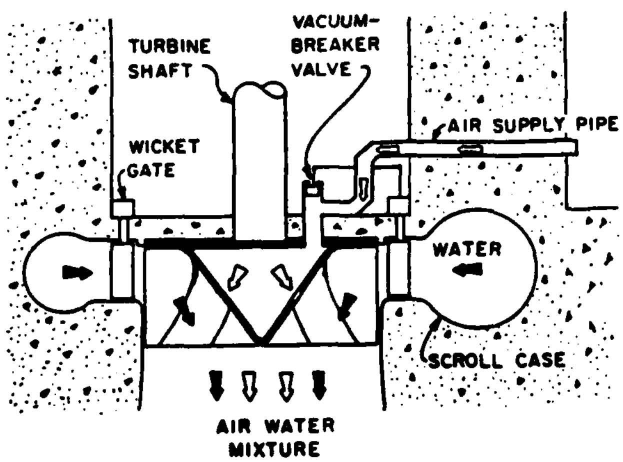


Figure 1. Vacuum-breaker venting system

29. The vacuum-breaker systems were not designed to transport large volumes of air. Usually, the piping system that provides air to

the turbine is long, with bends, elbows, and valves which cause a significant loss of energy as air flows through the venting network. This results in limitations on the flow rate of air that can be vented into the release flow. Modifications to existing venting system air-supply lines have increased air flow rates and enhanced gas transfer. One example of a modified supply line consists of a smooth bell-mouth intake that bypasses the vacuum-breaker system, as shown in Figure 2.

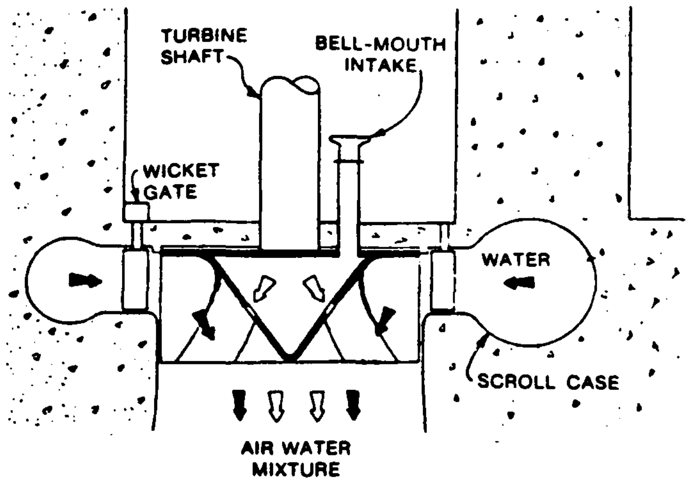
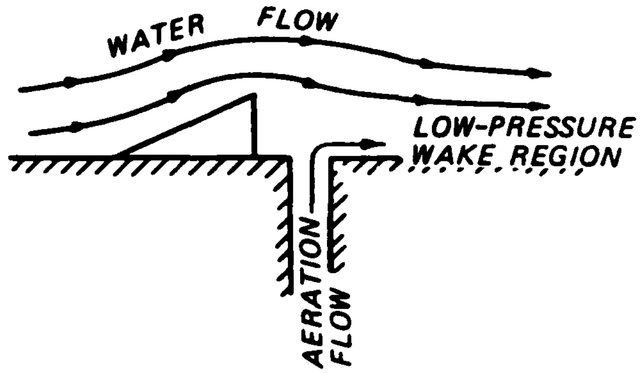
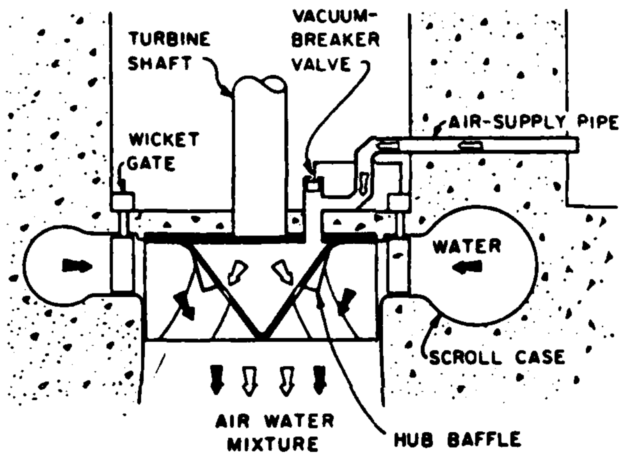


Figure 2. Large-diameter bell-mouth air intake

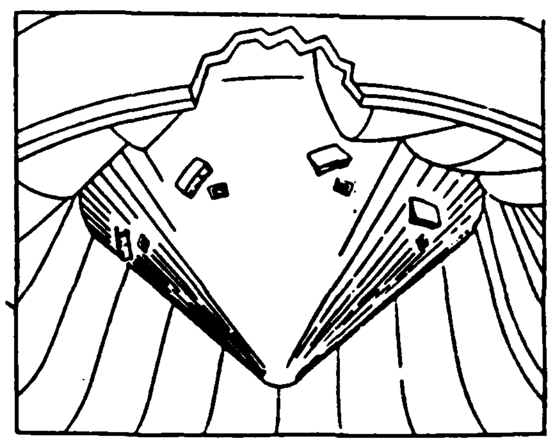
30. Generally at higher flow rates, the absence of low pressure in the draft tube prevents the natural aspiration of air. The deflector plate concept (Raney 1973) was developed to create or enhance negative gage pressures at the aeration ports on the turbine hub. Deflector plates are placed in the water flow upstream of port openings on the turbine hub in such a manner that flow separates from the turbine hub over the aeration portal. This separation creates low pressures at the aeration portal. Even when free stream gage pressure is positive, the deflector plates create negative pressure at the aeration port. The deflector plate also increases the magnitude of the negative gage pressures at the aeration port when negative free stream pressures occur during lower flow rates. The larger the negative gage pressure created by the deflector, the greater the rate of aspiration. Typical deflector design and location on the hub of a Francis turbine are shown in Figure 3.



a. Deflector plate design



b. Location of hub baffles



c. Distribution of baffles on hub

Figure 3. Typical deflector design and placement

31. The installation of deflector plates significantly enhances air aspiration, but increased hydraulic losses are incurred. The consequences of these losses are small reductions in turbine efficiency (at all operating levels) and a reduction in output capacity of the turbine. These losses translate to lost revenue. Thus, in many cases, turbine efficiency and DO enhancement are competing interests. Ideally, a deflector would be designed and placed to result in a minimum hydraulic head loss while maximizing the rate of aspiration. Because of the additional head loss caused by deflector plates, it could be advantageous from a power generation standpoint to remove the deflector plates during periods when DO enhancement is not needed.

32. Aspiration can also be induced downstream of the turbine in the draft tube. A manifold ring such as that shown in Figure 4, attached to the periphery of the draft tube liner, has been used to create or enhance negative pressures in the draft tube (TVA 1982) for essentially the entire range of turbine operation. Vent holes on the downstream side of the ring allow the aspiration of air into the release flow. Uniform spacing and appropriate sizing of the vent holes permit the uniform distribution of air around the ring.

33. The general advantage of all in-structure aeration techniques compared to forebay or tailwater systems is that all the outflow from a project must pass through a confined region. If the water quality can be enhanced in this area, it will impact the entire outflow from the project.

Air/oxygen injection

34. The second method of in-structure aeration uses an outside power source, such as compressor systems, to overcome the naturally occurring hydrodynamic pressures in the turbine to aerate the hydropower release water. In some instances, forced-air injection may be more attractive than induced aspiration since hydraulic losses due to deflectors are not experienced. Forced-air venting systems have the potential to aerate flows under all operating conditions. The rate of aeration can be varied to correspond with the degree of enhancement desired. Compressor systems can also be installed to inject air into

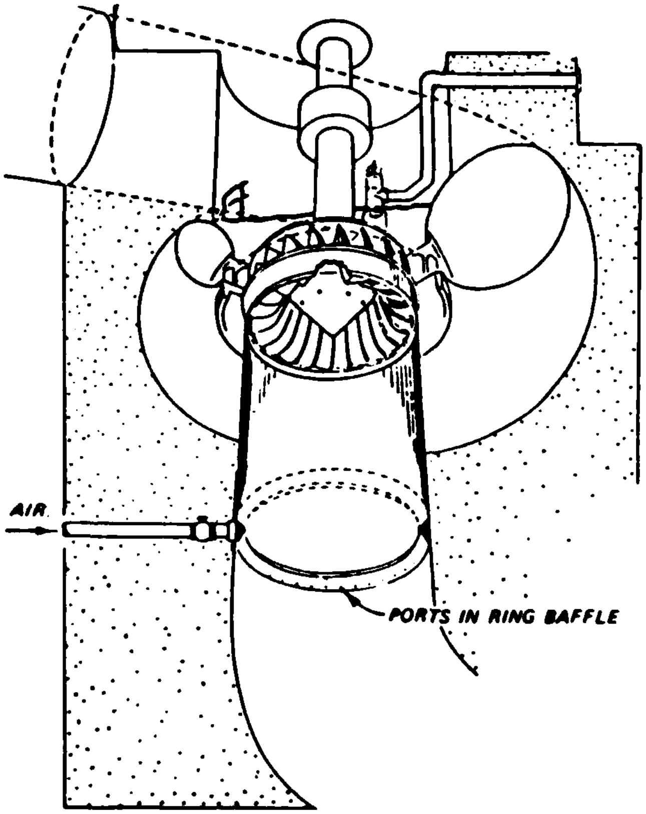


Figure 4. Schematic of ring baffles installed in draft tube

the penstock, resulting in longer contact times between the air bubbles and release water, thereby improving DO uptake. The disadvantages of a forced-air system are: (a) high initial cost of equipment (high volume/high-pressure compressors are quite expensive), and (b) the operation and maintenance costs of the compressor and delivery system. A schematic of a general compressor system is shown in Figure 5.

Recommended Technique

35. As indicated in previous paragraphs, Bohac et al. (1983) performed an extensive literature review on the alternatives available for improving the quality of water released from hydropower projects. More particularly, they identified many efforts to aerate release flow to

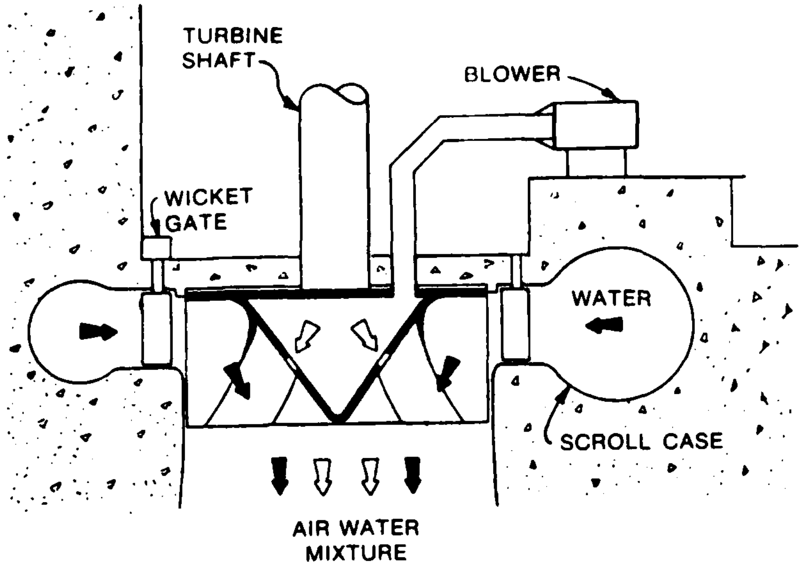


Figure 5. Schematic of forced-air injection system

improve DO. It is not the purpose of this report to detail their findings, but rather to use their information to more clearly define the techniques that are applicable to CE projects. Refinement of available information and data about a particularly attractive technique into guidance for evaluation and engineering design would then be in order.

36. No single hydropower aeration system is universally preferred. In general, for CE impoundments, forebay or in-structure aeration/oxygenation systems would be superior to tailwater systems. Because of the usually large discharges from a CE hydropower project, tailwater systems have limited applicability. In addition to improving release water quality, forebay systems usually improve in-lake water quality.

37. The Bureau of Reclamation routinely employs pneumatic destratification to maintain in-lake water quality in water supply reservoirs. The CE has employed a localized pneumatic destratification at Lake Allatoona, Georgia (USAED, Savannah 1969) for several years. A hypolimnion oxygenation system has been installed at Lake Richard B. Russell, Georgia/South Carolina, and commenced operation in spring 1985 (USAED, Savannah 1981a, 1981b, 1982). However, these systems may

require substantial size and capital outlay because of the large volume of in-lake water that must be improved.

38. Based on the review of Bohac et al. (1983) and prototype studies by Raney and Arnold (1973) and Mauldin (1982), turbine venting appears to be one of the most generally applicable techniques. Most CE projects are relatively high head and employ Francis-type turbines. These turbines (as well as the propeller type) are suitable for venting. Thus, this technique could potentially be applied at many projects.

39. The TVA and the Alabama Power Company (APC) have tested turbine venting at several hydropower projects. Deflector plates for aspirating air and blowers or compressors for forced-air injection were tested with varying degrees of success. Aspiration through the vacuum-breaker system normally resulted in relatively low DO enhancement. In most instances, increases in DO were less than 2 mg/ℓ, even with the vacuum breaker system blocked open. Deflector plates increased the air flow rate into the water discharge and thereby increased the oxygen absorption. When the vacuum-breaker system was bypassed, oxygen uptakes of 2.5 to 3.5 mg/ℓ with deflectors were observed. With a draft tube manifold ring, as discussed in paragraph 32, DO improvements of 3.5 mg/ℓ were reported.

40. As discussed earlier, a loss in turbine efficiency generally occurs when large volumes of air are injected or aspirated into the water flow. At Norris Dam, tests by the TVA indicated a loss of about 3 percent in turbine efficiency when deflector plates were used to aspirate air at a flow rate equal to 3 percent of the water flow rate. At full-gate operation, output capacity dropped by about 5.5 percent. Similar observations were made at test installations at APC hydropower facilities. Efficiency losses on the order of 2 percent were observed in conjunction with the installation of an aeration manifold ring. These losses are essentially a head loss; consequently, the percent loss associated with these alternatives may tend to decrease with increasing head.

41. The synthesis of design procedures to implement the turbine

venting alternatives (either aspiration or injection) is a necessary step in the application of turbine venting technology. Therefore, the physical processes that impact reaeration during turbine venting must be identified. Descriptions of these processes must be developed so that an accurate prediction of oxygen uptake can be made. Thus, an evaluation of the effectiveness of turbine venting can be accomplished for a specific stratification, discharge, and outlet geometry situation.

42. The relationship of turbine performance and turbine venting must be understood to determine the economic impacts of turbine venting. The remainder of this report presents the effort to further understand the processes and relationships that govern oxygen uptake with turbine venting and develop descriptions of those that can be used for evaluation and design guidance.

PART III: FIELD STUDIES FOR PROCESS DESCRIPTION

Field Study Site

43. As stated in previous paragraphs, adequate design guidance to implement a turbine venting system has not been completely developed. Hence, field studies were initiated to quantify the design aspects and more clearly define the impacts of turbine venting. Field studies were conducted at the Clarks Hill Dam on the Savannah River. The project has seven Francis-type turbines rated at a power capacity of 40 MW each. Clarks Hill Dam is a peaking power project; thus, the turbines are usually operated daily for 6 to 10 hr at levels from 35- to 100-percent capacity.

44. The vacuum-breaker venting system (described in paragraph 28) at this site consisted of a cam-operated valve and an 8-in.* air-supply pipe. The vacuum-breaker system operated at wicket gate openings below 43 percent. On the turbine hub, there were eight equally spaced 3- by 7-in. holes through which the vented air entered the flow.

45. Two turbine venting techniques were investigated: (a) aspiration and (b) injection. Aspiration was investigated on Unit 2 (no deflector plates) with the existing vacuum-breaker system forced open for the entire range of wicket gate settings. A second aspiration arrangement was tested by replacing the vacuum-breaker valve with a 10-in.-diam smooth bell-mouth intake. A final series of tests was conducted on Unit 2 in which air was forced into the turbine with a low-pressure (approximately 0.5 psi, although a high-pressure compressor would have proven more effective) 25-hp blower.

46. Unit 4 was fitted with deflector plates to decrease the pressure at the vent holes on the turbine hub. The deflector plate design was based on prior work by TVA (1981), Mauldin (1982), and the APC (Raney 1973, 1975). The deflectors on Unit 4 were constructed of stainless steel with a 45-deg leading angle. The deflector plate was

---

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

8 in. wide, 3 in. deep, and 3 in. high (Figure 6). The deflectors were oriented and welded in place on the hub about 4 in. upstream of the vent holes so that the lowest pressure in the wake of the deflector occurred over the vent holes (Mauldin 1982). Tests were conducted with the vacuum-breaker system blocked open. The second configuration tested on Unit 4 was the replacement of the vacuum-breaker valve with a bell-mouth intake to increase the air flow into the turbine.

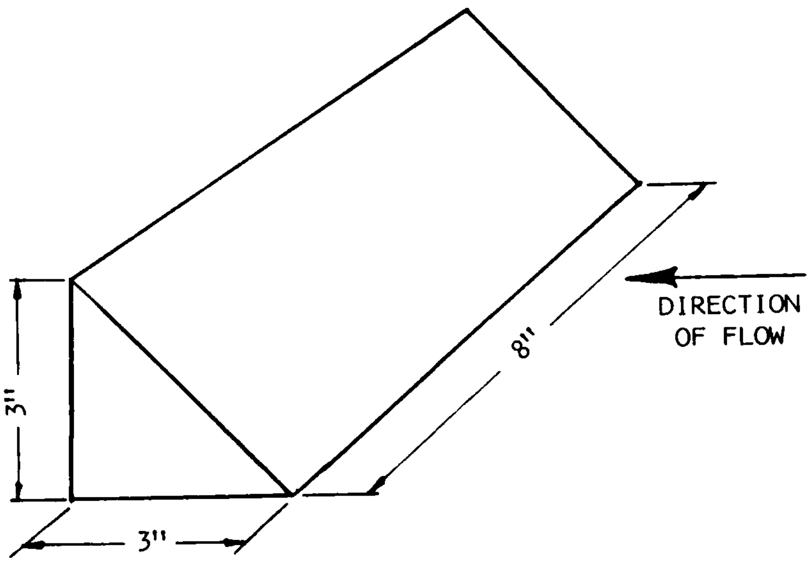


Figure 6. Deflector design

47. Both units were tested under "no-air" conditions, i.e., venting mechanisms held shut, to establish baseline performance data on turbine operation and oxygen absorption. The operating threshold at Clarks Hill powerhouse was 30 percent. Power production limitations prevented gate settings greater than 85 percent. Therefore, wicket gate settings ranged from 30 to 85 percent on all turbine venting tests.

Data Collection and Instrumentation

48. To develop engineering guidance for turbine venting, the processes that affect oxygen uptake and turbine performance must be understood. Further, for rigorous analyses, mathematical descriptions

of these processes have to be developed. By examining the effects of a process, often the cause can be identified. Thus, field data collection and analysis can produce, when coupled with appropriate theoretical analyses, the mathematical relationships for the processes that cause the effects. A greater understanding of those processes is thereby acquired.

49. The enhancement of DO concentrations in hydropower releases is the objective of turbine venting. Therefore, upstream (penstock) and downstream (tailrace) DO concentrations were measured.

50. When gas transfer occurs due to air bubbles in the water body, more air bubbles should result in more gas transfer. Thus, for turbine venting, the flow rate of air into the turbine significantly impacts the reaeration (oxygen uptake) process. The air flow into the turbine was determined for all the conditions tested. Additionally, since the air flow rate is affected by the pressure in the turbine and draft tube, the turbine head cover pressure was measured.

51. For any hydraulic situation when air is entrained or injected into a pressure flow (draft tube) condition, the potential exists for gas supersaturation to occur. Total dissolved gas pressure, from which the level of saturation can be determined, was also measured. For complete analysis of dissolved gas saturation and to determine the level of nitrogen saturation, DO, water temperature, and barometric pressure data are required.

52. Power output, water flow rate, and headwater and tailwater elevations were collected to evaluate the impact of injected or aspirated air on turbine operation. These turbine performance data are required to calculate the operating efficiency of the turbine. Wicket gate settings which indicate the level of turbine operation were recorded. From these data, a comparison of the various aeration techniques and associated impacts on turbine operation can be performed.

53. Data were collected from several locations at the dam. The tailrace (downstream) data collection point was located in the turbine release downstream of the aeration bubble plume. Simultaneous data collection at each of the collection points was accomplished by use of

portable radio communication. Table 1 lists the data types collected in these field studies and describes the measurement techniques used in their collection.

Table 1

Data and Method of Calculation

Parameter	Method of Collection
Penstock and DO (mg/ℓ)	Yellow Springs Instrument Co. (YSI) polarographic DO probes (calibrated with the Modified Winkler method).
Water temperature (^{o}C)	Water temperature was measured with mercury thermometers and the YSI probe.
Barometric pressure (mb)	Readings were made three times daily with a portable barometer.
Air flow rate (cfs)	An air-velocity profile was measured with a hot-wire anemometer, or a Pitotstatic tube and manometer. Air flow rate was determined by integrating the point velocity readings over the area of the conduit.
Head cover pressure (ft water)	A pressure gage was read at the turbine.
Total dissolved gas pressure (TDGP) (mm HG)	A saturometer designed at WES (Wilhelms 1984) was used to measure TDGP. Total nitrogen concentration was calculated from TDGP readings and DO readings by assuming all gas in the water that was not oxygen was nitrogen.
Power output (MW)	Revolutions of the watt-hour meter in the control room were counted over timed intervals.
Water flow rate (cfs)	Readings were taken from a differential manometer connected to Winter-Kennedy pressure taps on the turbine scroll case and from a digital flow rate meter in the control room.
Headwater and tailwater elevations (ft)	Readings were taken from meters in the control room.
Wicket gate opening (% open)	Readings were made from a meter in the control room and from indicators on the turbine.

Note: Tables A1-A7 of Appendix A present data from the 1982 field studies. Tables A8-A9 present data from the 1981 field studies.

PART IV: RESULTS OF FIELD TESTING

Data Reduction

54. To permit comparative analyses of the Clarks Hill data, the power output and discharge measurements were adjusted to a gross head of 146 ft. The following relationships (Pfau 1948) were used in making these adjustments.

$$\frac{P_{ADJ}}{P_{ACT}} = \left(\frac{H_{ADJ}}{H_{ACT}}\right)^{3/2} \tag{1}$$

$$\frac{Q_{ADJ}}{Q_{ACT}} = \left(\frac{H_{ADJ}}{H_{ACT}}\right)^{1/2} \tag{2}$$

where

P_{ADJ}, Q_{ADJ} = power output and flow rate, respectively, adjusted to 146-ft head

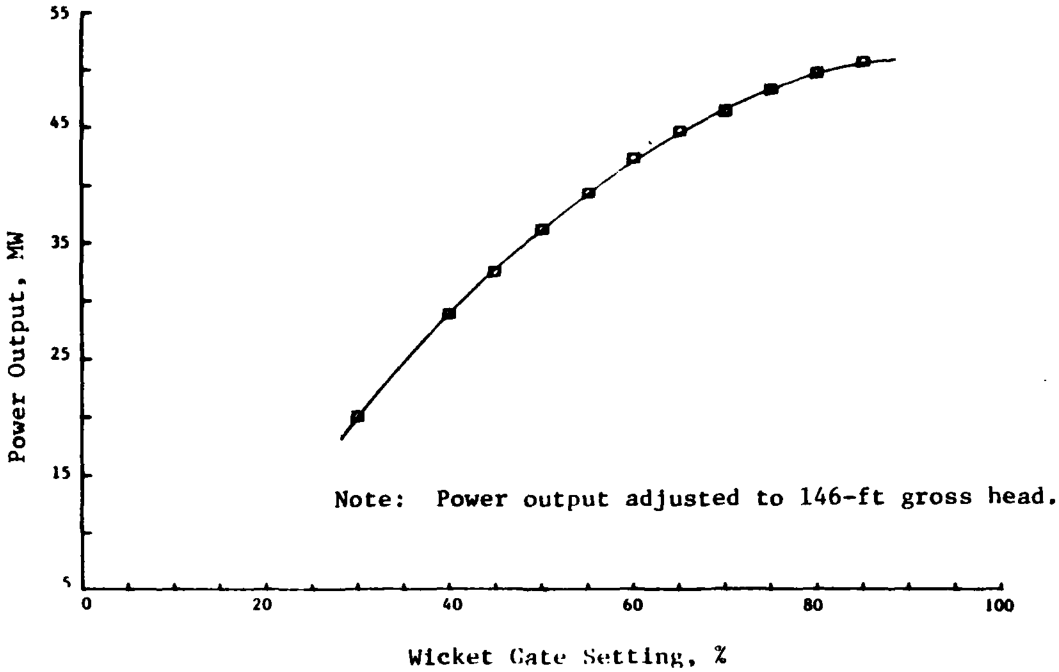
P_{ACT}, Q_{ACT} = observed power output and flow rate, respectively

H_{ADJ} = adjusted gross head, 146 ft

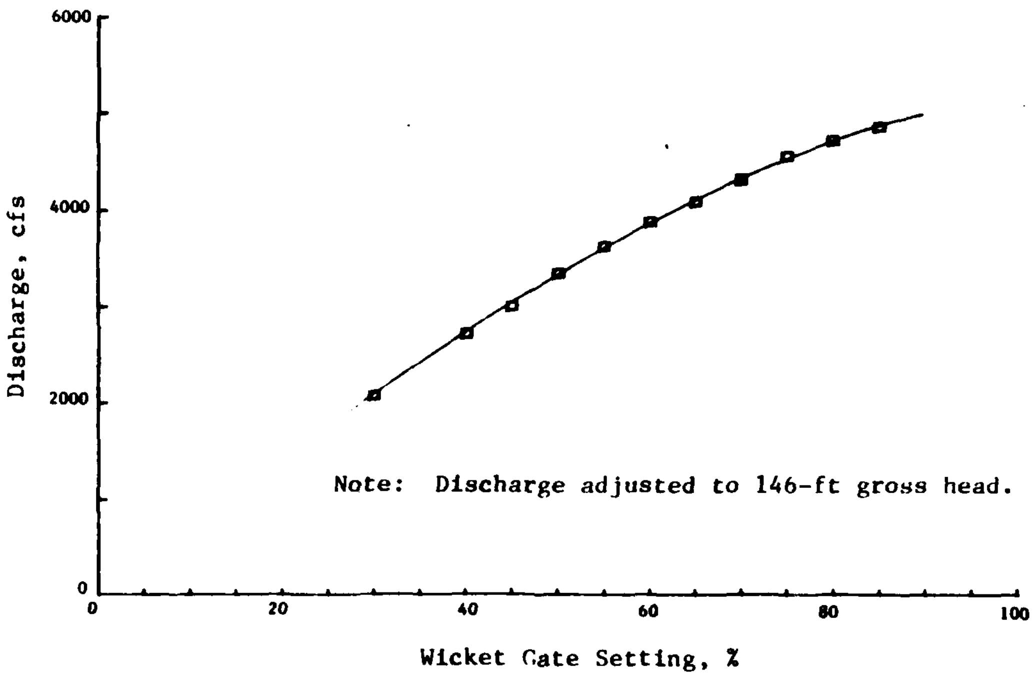
H_{ACT} = observed gross head, ft

55. For each condition tested, the adjusted data were plotted against wicket gate opening to facilitate analysis. Figures 7a and 7b show the power and discharge graphs, respectively, for Unit 2, without air injection or aspiration. These plotted data were smoothed by hand, as indicated by the solid lines. Subsequently, "smoothed" power, discharge, and wicket gate data were digitized from these curves and were used in process analyses. Plots similar to Figures 7a and 7b for all the venting techniques (Units 2 and 4) are presented in Figures B1-B14 of Appendix B.

56. Turbine efficiency was calculated using the following relationship:



a. Power output versus wicket gate



b. Discharge versus wicket gate

Figure 7. Power and discharge graphs, Unit 2, no air flow

$$E = \frac{KP}{QH} \tag{3}$$

where

E = turbine efficiency, percent

K = conversion factor, ft^4/sec - MW

P = power output, MW

Q = turbine discharge, cfs

H = headwater elevation-tailwater elevation, ft

The K term has a value of $1.18\ (10^6)$ and accounts for the conversion of units and the effects of power transformers. In this computation, the P and Q values were digitized from the smoothed plots of power and discharge versus wicket gate setting, respectively.

Analysis of Turbine Performance

57. As stated previously, air flow rate was considered to be an important parameter affecting DO uptake. Air flow rate was also found to significantly impact turbine performance (Raney 1973; Buck, Miller, and Sheppard 1980; Mauldin 1982). Thus, to evaluate that impact, the no-air test results were used as the base condition for analysis of turbine efficiency changes. Turbine efficiency, as computed with Equation 3, was plotted against wicket gate setting for the no-air condition and for each of the venting arrangements. Figure 8 shows efficiency versus wicket gate for the no-air tests and the blower tests on Unit 2. Similar plots were developed for each of the venting techniques on Units 2 and 4 and are shown in Figures B15-B19. This difference in the efficiencies (between vented and no-air conditions) shown on these plots is indicative of the impact of venting (air injection or aspiration) on turbine performance.

58. These figures indicate that, in general, air introduction caused a small loss in efficiency compared to the nonvented condition. The loss was particularly pronounced for the lower (less than 50-percent) wicket gate openings when relatively large volumes of air were being drawn or forced into the turbine. Referring to Figure 8, the loss

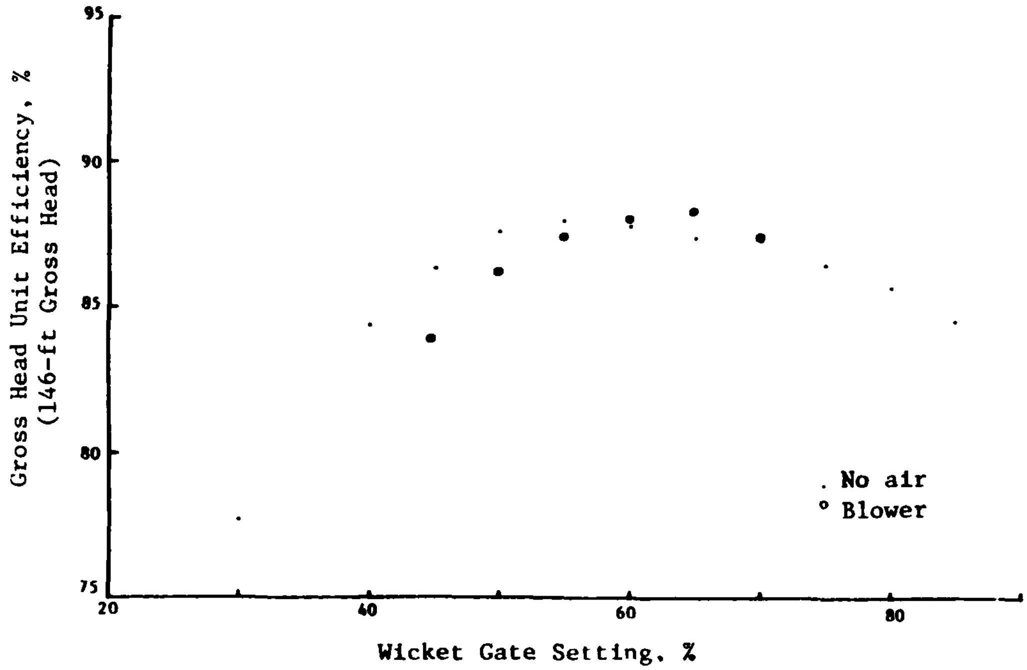


Figure 8. Efficiency versus wicket gate, Unit 2

experienced by the Unit 2 turbine at a 45-percent wicket gate was about 4 percent. At a 55-percent wicket gate, the loss was about 1.5 percent. Similar trends are apparent from the other venting test conditions by examining Figures B15-B19.

59. It should be noted that this efficiency loss is a real loss in power output and not "power deferred," i.e., a decrease in discharge that "saves" water for later power production. Plots of turbine efficiency versus discharge (Figures B20-B24) such as that shown in Figure 9, clearly demonstrate that the loss in efficiency was not offset by a corresponding decrease in discharge rate. A 1-percent loss in efficiency would be accompanied by a 1-percent decrease in discharge rate if the "power deferred" concept were applicable for these techniques.

60. Of particular interest in Figure 8 is the slight efficiency increase at and above a wicket gate setting of 60 percent for the vented condition compared to the no-air condition. At these gate settings, the air flow rates were small relative to the water flow rates, compared to those at the lower gate settings (Figure 10). The improved performance

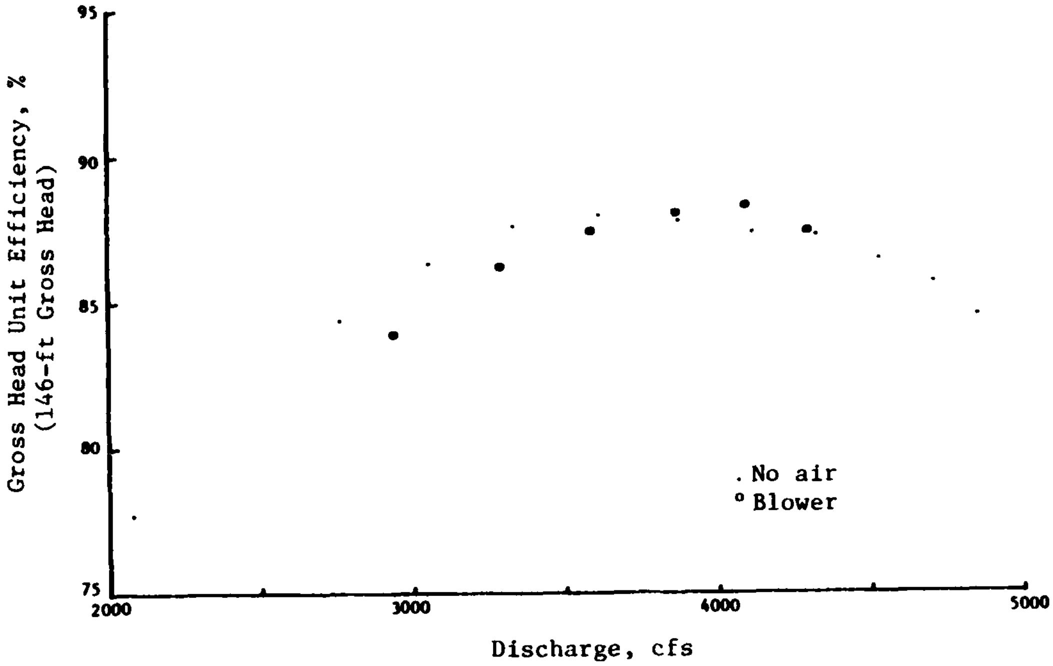


Figure 9. Efficiency versus discharge, Unit 2

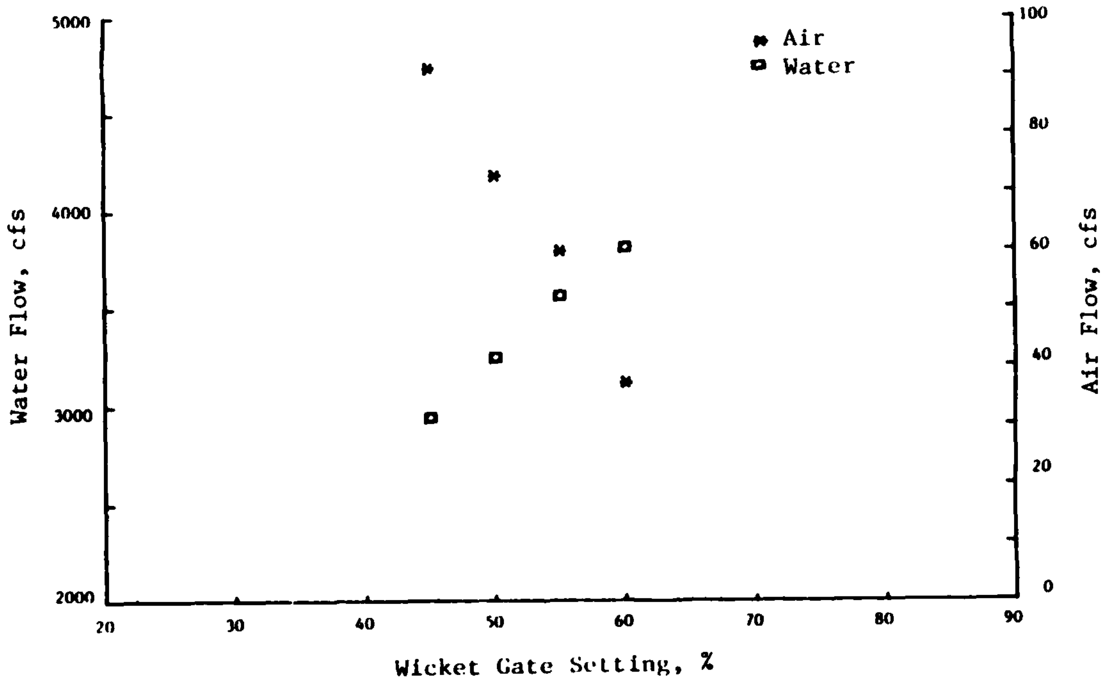


Figure 10. Air flow and water flow versus wicket gate, Unit 2, blower

can probably be attributed to smoother turbine operation resulting from the introduction of the small air volume. In an analysis of Figures 8 and 10, it can be concluded that air, vented into the turbine, can improve or degrade the performance of the turbine depending upon the amount of air.

61. To permit a more general analysis of the effects of injected or aspirated air on the turbine performance, the air flow parameter was nondimensionalized by dividing it with the water flow rate. Thus, an air flow-to-water flow ratio of 0.02 means that air flow was 2 percent of the water flow.

62. To obtain these ratios, observed air flow (Q-air) and observed water discharge (Q-water) data were plotted against wicket gate opening in Figure 10 for the Unit 2 blower tests. Similar graphs for each of the venting techniques are presented in Appendix B (Figures B25-B29). Flow rate information at any given gate setting was interpolated or extrapolated from observed data.

63. By referring to the efficiency curves shown in Figures 8 and B15-B19 and the air flow and water flow curves shown in Figure 10 and B25-B29, for a given wicket gate opening an air flow-to-water flow (Q-air/Q-water) ratio and an efficiency loss can be determined. Plotting efficiency loss against the ratio of air flow to water flow for Unit 2 (Figure 11) shows the change in turbine performance due to venting air into the turbine. In most tests an efficiency loss was observed; however, at very small Q-air/Q-water ratios, a slight efficiency improvement was observed for Unit 2. As stated earlier, this was probably the result of smoother turbine operation due to the introduction of very small air volumes.

64. For Unit 2, without deflector plates, the efficiency loss was linearly related to Q-air/Q-water except for the tests of the vacuum-breaker system. It appears that this nonlinearity was due to the flow characteristics of the vacuum-breaker system, i.e., air flow was limited (compare air flow in Figure B25 and the vacuum-breaker efficiency loss in Figure 11). Figure 12 shows efficiency loss plotted against Q-air/Q-water for Unit 4 (the turbine with deflectors). This

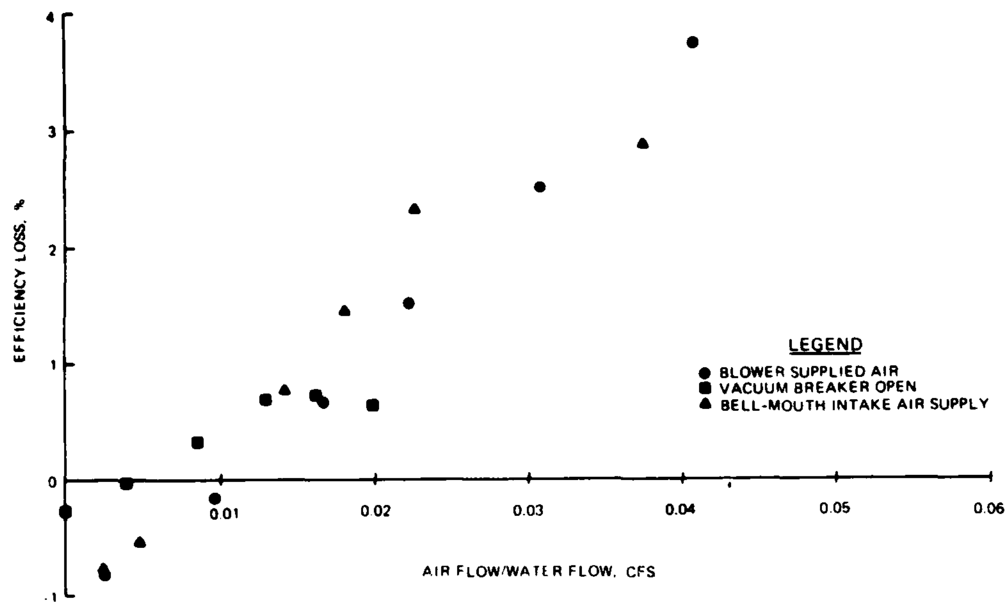


Figure 11. Efficiency loss versus air flow-to-water flow ratio, Unit 2

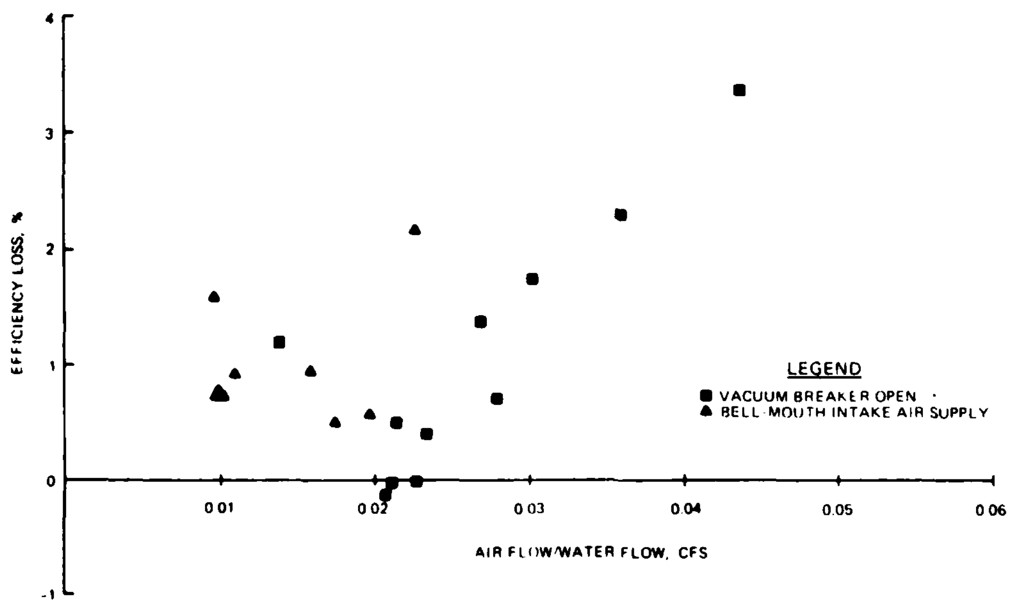


Figure 12. Efficiency loss versus air flow-to-water flow ratio, Unit 4

graph indicated that there was nearly always an efficiency loss. This maybe a consequence of the relatively large volumes of air that were aspirated into the turbine over the entire range of wicket gate settings (Figures B28-B29) as a result of the deflectors or a combined effect of the air and the hydraulics of the deflectors.

Analysis of Oxygen Transfer Characteristics

65. To analyze the DO uptake due to turbine venting, an understanding of the physics that affect gas transfer is necessary. The force driving the gas transfer process is the difference in partial pressure of the oxygen in the water and in the air at the air/water interface. If the partial pressures of oxygen in the water and in the air are equal, then no driving force exists and the net oxygen transfer between the air and the water is zero. Under this thermodynamically equilibrated condition, the water is considered "saturated." If the partial pressures in the water and in the air are unequal, then a force exists to cause an oxygen transfer.

66. A measure of this force is the "saturation deficit," which can be quantified by using the concentration of the oxygen in the water and the saturation concentration defined by Henry's Law (Schroeder 1977)

$$C_s = kp \tag{4}$$

where

C_s = saturation concentration for oxygen
k = proportional coefficient for oxygen
p = partial pressure of oxygen in atmosphere across air/water interface

Henry's Law simply states that water (at a given temperature) can contain an amount of DO that is linearly proportional to the partial pressure of that gas in the atmosphere across air/water interface. The "saturation deficit" is the difference between the saturation concentration and the actual concentration of oxygen in the water and is describe by

$$D = C_s - C_a \tag{5}$$

67. Reaeration or oxygen uptake is usually considered to be a first-order reaction that is described in in terms of initial and final (or upstream and downstream) saturation deficits. Therefore, the oxygen transfer characteristics of turbine venting were analayzed on the basis of the relationships between the upstream and downstream deficits and the air-to-water flow ratio. To nondimensionalize the quantities, a "deficit ratio" was defined as the ratio of the downstream deficit (DO deficit of water leaving vicinity of tailrace area) to the upstream deficit (DO deficit of water in penstock).

68. Figure 13 shows the relationship between deficit ratio and Q-air/Q-water. Least squares regression analysis of these data resulted in

$$\frac{C_s - C_d}{C_s - C_u} = \frac{D_d}{D_u} = 0.67 + 0.424\ e^{-70.9r} \tag{6}$$

where

C_s = temperature-dependent saturation concentration of oxygen

C_d, C_u = downstream and upstream DO concentrations, respectively

D_d, D_u = downstream and upstream DO deficits, respectively

r = air flow-to-water flow ratio

Figure 13 clearly indicates that the oxygen transfer characteristics of turbine venting are a function of Q-air/Q-water. The scatter in the data suggests that other conditions also impact oxygen uptake.

69. Figure 13 and Equation 6 suggest that there is a maximum reduction in deficit ratio which can be achieved with turbine venting. The exponential term in the equation becomes very small as the air flow-to-water flow ratio increases. This indicates that with a large r, the downstream deficit would be about 70 percent of the upstream deficit. For example, if the upstream deficit was 8.0 mg/ℓ, the downstream deficit would be approximately 5.6 mg/ℓ (Df/Di = 0.70) if the

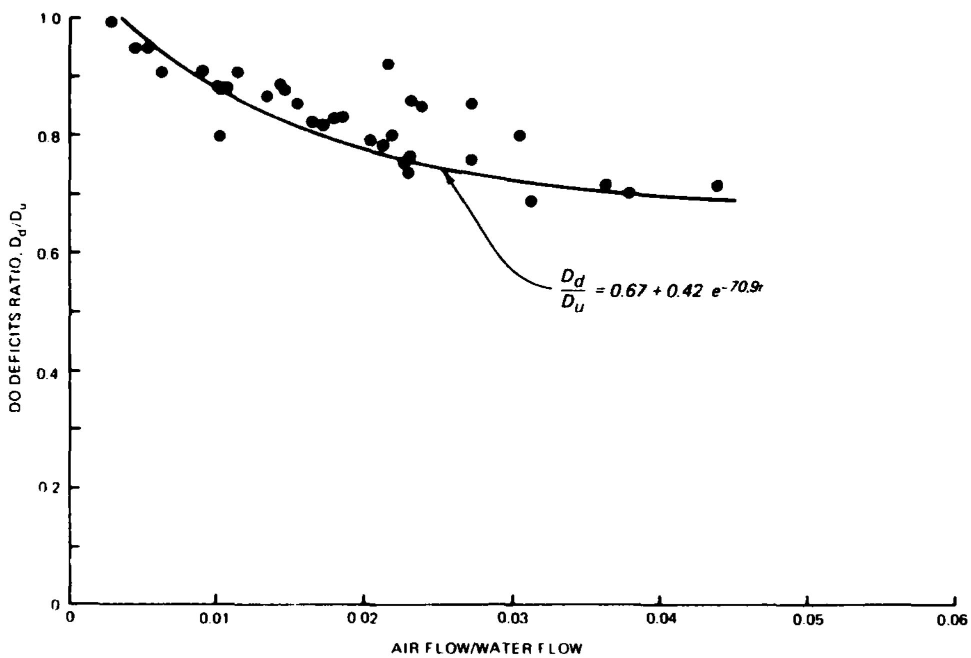


Figure 13. Deficit ratio versus air flow-to-water flow ratio (Q-air/Q-water)

air flow was 3.7 percent of the water flow (Q-air/Q-water = 0.037). A DO uptake of 2.4 mg/ℓ would be experienced under these condition. Further, Equation 6 and Figure 13 indicate that even with 6-percent air flow, the oxygen uptake would increase to only 2.6 mg/ℓ. Thus, further increases in air flow may produce only marginal impacts on the DO concentration of the release.

Comparison of Techniques

70. A comparison of the venting systems for each of the turbines is presented in Table 2. Wicket gate settings of 40, 50, and 60 percent were selected as the settings at which comparisons could be made. At these gate openings, all the conditions (no-air, vacuum breaker, bell-mouth intake, and blower) were tested on Unit 2, with the exception of the blower at 40-percent gate opening; all the techniques except the blower were tested on Unit 4. To compare the oxygenation capabilities of each system, the percent of deficit satisfied is shown in Table 2.

The deficit satisfied is the difference between the upstream and downstream deficits divided by the upstream deficit.

$$S_D = \frac{D_u - D_d}{D_u} = 1 - \frac{D_d}{D_u} \tag{7}$$

where S_D = deficit satisfied.

71. Referring to the example discussed in paragraph 69, if the downstream deficit was 70 percent of the upstream deficit, then

$$\frac{D_d}{D_u} = 0.70 \tag{8}$$

and

$$S_D = 1 - 0.70 = 0.30$$

or 30-percent deficit satisfaction was achieved. Efficiency change is also shown in Table 2. These values were computed by

$$\Delta E = E_o - E_c \tag{9}$$

where

ΔE = efficiency change, percent

E_o = efficiency of turbine under no-air condition, percent

E_c = Efficiency of turbine under each venting technique, percent

Although the values presented in Table 2 represent individual test results, they provide a basis for comparing the systems in general terms.

72. From the table, the trade-offs between efficiency and gas transfer become obvious. Generally, the higher efficiency losses are associated with larger deficit satisfaction (more oxygen uptake). For example, on Unit 2, at a wicket gate setting of 50 percent, the vacuum breaker resulted in an efficiency loss of 0.7 percent with 19 percent of

Table 2

Comparison of Venting Systems

	Wicket Gate Setting, Percent								
	40			50			60		
Venting System	Eff. Chg.* %	Upstream DO Deficit mg/ℓ	Deficit Satisfied** %	Eff. Chg. %	Upstream DO Deficit mg/ℓ	Deficit Satisfied %	Eff. Chg. %	Upstream DO Deficit mg/ℓ	Deficit Satisfied %
Unit 2									
No air	0	9.2	4	0	8.9	1	0	8.9	2
Vacuum breaker	-0.6	9.1	25	-0.7	9.2	19	+0.1	8.9	8
Bell mouth	-2.9	8.9	35	-1.3	9.2	23	+0.7	9.2	12
Blower	-3.2†	8.8†	N/A	-1.3	8.8	26	+0.3	8.9	15
Unit 4									
No air	0	9.1	6	0	9.2	5	0	9.2	9
Vacuum Breaker	-2.2	9.1	33	-0.5	9.2	27	-1.2	9.2	17
Bell mouth	-3.3	8.9	34	-1.6	9.2	29	-1.2	9.2	21

* Eff. Chg. (ΔE) = efficiency change, in percent, as compared to the no-air base efficiency for that unit.

** Deficit Satisfied (S_D) = upstream deficit satisfied, in percent.

† These data were collected at 45-percent wicket gate opening and therefore cannot be compared directly with other data in the same column.

the deficit satisfied. Replacing the vacuum breaker with the bell-mouth intake allowed more air flow, and the deficit satisfied increased to 23 percent. However, the efficiency loss increased as well, to 1.3 percent.

73. An increase in turbine efficiency at a wicket gate setting of 60 percent was observed on Unit 2 for all systems tested. The gas transfer at this setting was very small, as might be expected for the very low air flow being vented into the turbine (see Figures B25-B27). Thus, benefits of improved efficiency and significant gas transfer cannot be realized simultaneously. The increased efficiency was not observed for any test on Unit 4. This may have been caused by the presence of deflectors and/or the large air flow rate (Figures B28-B29). The turbine efficiency losses and gas transfer were generally greater with deflectors than without.

74. Based on system comparison, use of the vacuum breaker has a moderate impact on both efficiency and gas transfer. However, when coupled with deflectors, the effects are significantly increased. Using the bell-mouth intake in place of the vacuum-breaker system significantly decreased the efficiency in the lower range of wicket gate settings. Since these low wicket gate settings are generally not used for power generation, these efficiency losses may be inconsequential. At higher wicket gate settings, the moderate increase in gas transfer associated with the bell-mouth intake, compared with the vacuum-breaker system, may warrant accepting the slight decrease in efficiency. There was little difference between the effects of the bell-mouth intake and blower since the small blower (7,000 cfm air at 0.5 psi) did not significantly increase the air flow above the air flow rate with the bell-mouth intake (Figures B26-B27).

PART V: MODELING OF REAERATION THROUGH A VENTED HYDROTURBINE

75. Development of a technique to predict the oxygen uptake due to turbine venting is requisite for subsequent development of engineering design guidance. The technique must include in its formulation factors that account for as many of the actual physical processes as possible. If the predictive technique accurately models the processes, the potential effects of a proposed turbine venting installation could be evaluated. If the impact of turbine venting could be estimated, the costs (in terms of efficiency loss) of the increased oxygen in the release could be determined and alternatives compared. This application will be discussed with an example in the concluding section of Part V.

76. The data discussed in Part IV and presented in Appendix A give us only the results of the various processes affecting release DO. Thus, it is necessary to identify each process and the impacts of each. Once this is accomplished, a mathematical description of each process can be developed. Ultimately, the process descriptions must be combined to produce a complete mathematical model of the reaeration effects of turbine venting. This numerical model can then serve as a predictive technique with which proposed turbine venting may be evaluated. The following section shows the development of a numerical model of reaeration due to turbine venting.

Model Development

77. Analysis of the data from the no-air tests indicated that there was a DO uptake in the release in the tailrace area. When the turbine was vented and air was introduced into the flow (by aspiration or injection), additional DO uptake was observed. It was concluded that two processes were causing gas transfer. Turbulent reaeration in the tailrace was responsible for the oxygen uptake during the no-air tests. The additional uptake, during venting, was due to oxygen transfer from the injected air to the release water. Figure 14 shows the conceptual

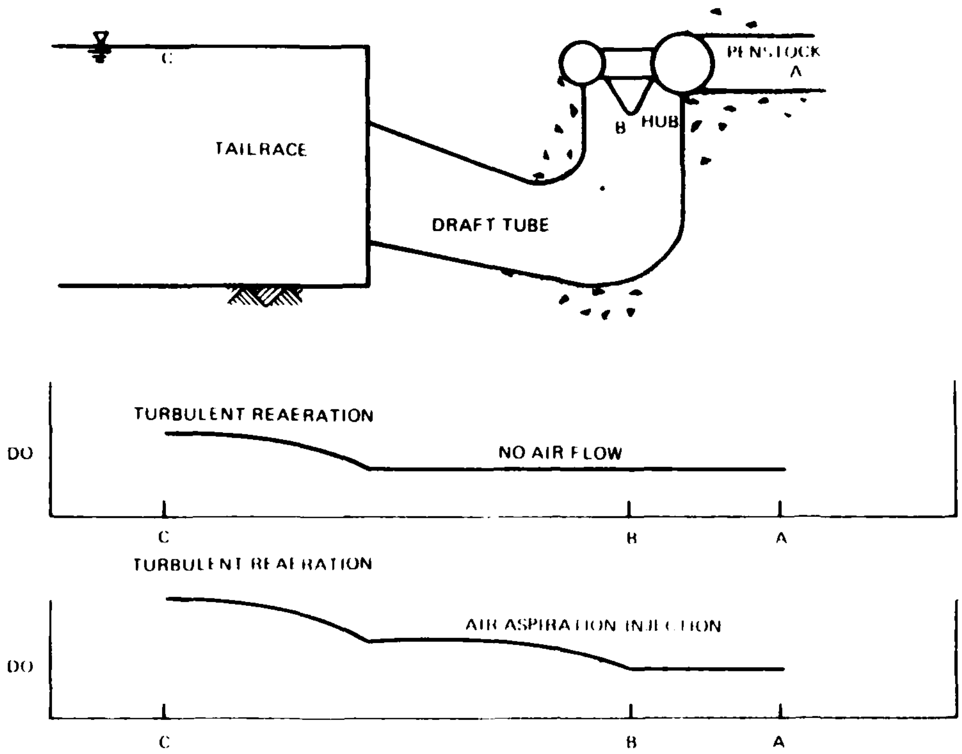


Figure 14. Conceptual relationship of gas transfer processes

relationship of these two processes. For development of the predictive model, the effects of these processes were mathematically described and superimposed to form a numerical model of the DO uptake due to turbine venting.

78. Turbulent reaeration in the tailrace area was considered a function of the available energy at the draft tube exit. The Energy Dissipation Model (EDM) (Tsivoglou and Wallace 1972, Wilhelms and Smith 1981) was used to account for the DO uptake during the no-air tests. The EDM describes reaeration by

$$\frac{C_s - C_d}{C_s - C_u} = \frac{D_d}{D_u} = e^{-c_T \Delta E} \qquad (10)$$

where

C_s = saturation concentrations for ambient water temperature T, mg/ℓ

C_d, C_u = tailrace and penstock DO (without venting), mg/ℓ

D_d, D_u = tailrace and penstock oxygen deficits, mg/ℓ

ΔE = energy dissipation coefficient, ft^{-1}

c_T = energy dissipated in tailrace, ft-lb/lb

79. The energy dissipated in the tailrace can be approximated by writing Bernoulli's equation at the draft tube outlet and at a point in the tailrace downstream of the high-turbulence area.

$$\frac{P_{DT}}{\gamma} + \frac{\left(V_{DT}\right)^2}{2g} + Z_{DT} = \frac{P_{TR}}{\gamma} + \frac{\left(V_{TR}\right)^2}{2g} + Z_{TR} + \Delta E \qquad (11)$$

where

P_{DT}, P_{TR} = pressure at draft tube (DT) center line and mid-depth in the tailrace (TR), respectively, lb/ft^2

γ = specific weight of water, 62.4 lb/ft^3

V_{DT}, V_{TR} = average velocity at DT and TR, respectively, ft/sec

g = acceleration due to gravity, 32.2 ft/sec^2

Z_{DT}, Z_{TR} = elevation above arbitrary datum for location at DT and TR, respectively, ft

80. The variables are also defined in Figure 15. It was assumed that the difference in water surface elevations between these two points was negligible, thus

$$\frac{P_{DT}}{\gamma} + Z_{DT} \approx \frac{P_{TR}}{\gamma} + Z_{TR} \qquad (12)$$

It was further assumed tha tthe downstream velocity was very small relative to dreft tube velocity, i.e., $\left(V_{TR}\right)^2/2g \approx 0$. Thus, the energy dissipated in the tailrace can be approximated by

$$\Delta E = \frac{\left(V_{DT}\right)^2}{2g} \qquad (13)$$

81. The energy dissipation coefficient is dependent on temperature (Churchhill, Elmore, and Buckingham 1962; Tsivoglou and

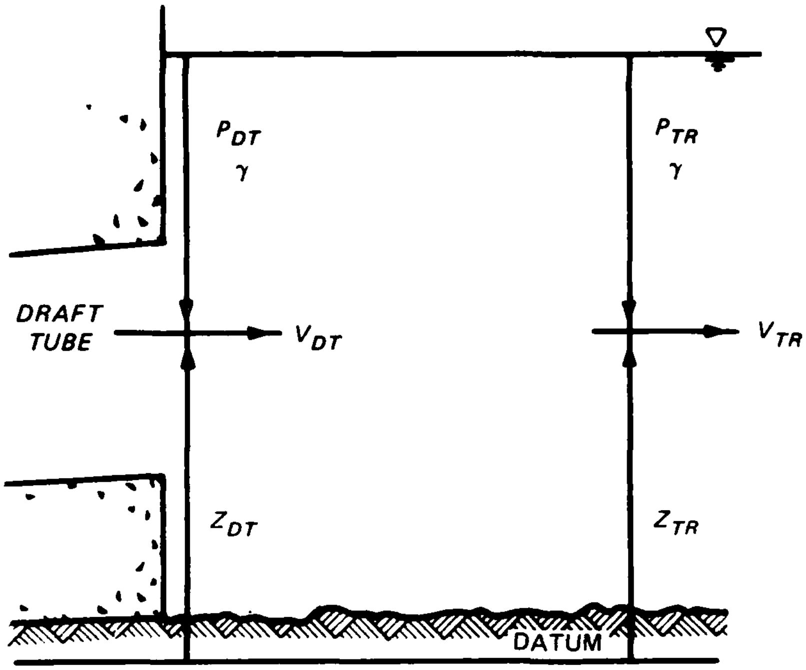


Figure 15. Variable definitions for Bernoulli equation

Wallace 1972) and the relationship is described by

$$c_T = c_{20}(1.024)^{(T-20)} \tag{14}$$

where

c_T, c_{20} = energy dissipation coefficient for water temperatures of (ambient) and 20° C, ft^{-1}

T = ambient water temperature, °C

Substituting Equations 13 and 14 into Equation 10 results in the following mathematical description of reaeration due to downstream turbulence.

$$D_d = D_u \exp\left[\frac{-c_{20}(1.024)^{(T-20)}\left(V_{DT}\right)^2}{2g}\right] \tag{15}$$

82. Using the observed DO readings from the no-air tests and continuity

$$V_{DT} = \frac{Q}{A_{DT}} \tag{16}$$

where

Q = discharge, cfs

A_{DT} = cross-sectional flow area of draft tube exit, ft^2

to determine draft tube velocity, a least squares regression analysis produced a c_{20} value of 0.15 per foot. The resulting equation can be used as a reaeration model when venting is not in operation. It must be remembered that the turbulent reaeration that occurred in the tailrace exists with or without venting. Thus, when venting is employed, this oxygen transfer must still be included, as shown in the conceptual model in Figure 14.

83. As stated earlier, the release DO improved significantly when venting was initiated compared to the no-air condition. Thus, the gas transfer occurring as a result of the vented air is the process that must be described. The discussion of DO uptake (paragraphs 65-69) concluded that the reaeration due to venting was a function of the ratio of air flow to water flow. Ordinarily, the gas transfer process is considered to be a first-order reaction and, as such, is mathematically described by

$$\frac{D_d}{D_u} = e^{-Kt} \tag{17}$$

where

K = exchange coefficient, sec^{-1}

t = time of flow from an upstream location to a downstream location, sec

84. A linear relationship between the exchange coefficient and r (Q-air/Q-water) was assumed.

$$K = ar \tag{18}$$

where

a = coefficient of gas transfer, sec^{-1}

r = ratio of air flow to water flow, dimensionless

Hence, Equation 17 becomes

$$\frac{D_d}{D_u} = e^{-art} \tag{19}$$

To apply Equation 19, the effects of hydraulic forces must be estimated as well as the travel time from an upstream point to a downstream point.

85. The hydraulic forces that act on the air bubbles as they travel from the venting port on the turbine hub to the tailrace must be understood. Those forces change the thermodynamic state of the air bubbles as they move through the draft tube and thereby impact the gas transfer from the bubbles to the water. Consider the thermodynamic state of an air bubble at the surface of a water body. The sum of the partial pressures of the gases that comprise the bubble is essentially atmospheric pressure; therefore, the partial pressure of oxygen in the bubble is equal to the partial pressure of oxygen in the atmosphere.

86. According to Henry's Law (Equation 4), an oxygen saturation concentration for the water surrounding the bubble can be determined. If the oxygen concentration in the water surrounding the bubble is equal to the saturation concentration, the oxygen gas in the bubble and in the water is at thermodynamic equilibrium which is characterized by no net oxygen transfer from the bubble to the water.

87. If the air bubble is forced deeper into the water body, the hydrostatic pressure acting on the bubble will increase with an identical increase in the pressure of the air inside the bubble. The increase in bubble pressure also increases the partial pressures of the gases that make up the air. According to Henry's Law, there would be a proportional increase in the saturation concentration. For example, at the surface of an impoundment, for a water temperature of 28° C, the saturation concentration for oxygen is 8.0 mg/ℓ. At a depth of 34 ft, the hydrostatic pressure is approximately twice that at the impoundment surface. Thus, the partial pressure of oxygen at this depth is twice

that at the surface. Hence, according to Henry's Law, the saturation concentration is 16.0 mg/ℓ.

88. This effect of hydrostatic pressure is important in defining the reaeration process during venting because the vented air travels with the discharge water downward in the draft tube below the turbine. As the air bubbles travel downward, they experience increased hydrostatic pressure and, as a result, their partial pressures increase. At this thermodynamic state, the saturation deficit, which is a measure of the force driving oxygen transfer, is larger than at atmospheric pressure. Since the deficit is larger, more oxygen can be transferred to the water. Thus, increased hydrostatic pressure on air bubbles improves the oxygen transfer, and the mathematical description of the reaeration process due to vented air must include these hydraulic conditions.

89. Buck, Miller, and Sheppard (1980) developed the concept of a "pressure-time history" of flow to account for the changes in hydrostatic pressure as flow passes through the draft tube. To develop such a history, a representative water flow rate for the turbine is chosen. Bernoulli's equation (Equation 11) and the continuity equation (Equation 16) are then applied to the flow through the draft tube to compute pressures at several locations and travel times between them. Using these computations and assuming atmospheric pressure exists at the venting port on the turbine hub, the time of travel for an average water particle can be plotted against the pressure which it experiences. This is termed the "pressure-time history." Figure 16 shows the pressure-time history for Clarks Hill.

90. While it is realized that the time-of-travel of a water particle through a draft tube is flow rate dependent, the magnitudes of the hydrostatic pressures are position dependent only; thus, the time value for the history can be linearly scaled according to the actual turbine discharge. For a discharge that is smaller than the one selected for history development, the time values would be adjusted with

$$t_a = t_s \frac{Q_s}{Q_a} \qquad (20)$$

where

t_a = adjusted time of flow for discharge Q_a, sec

t_s = time of flow for selected discharge Q_s, sec

Q_s = selected discharge for pressure-time history development, cfs

Q_a = actual turbine discharge, cfs

This adjustment to the pressure-time history allows its application to the range of turbine operation.

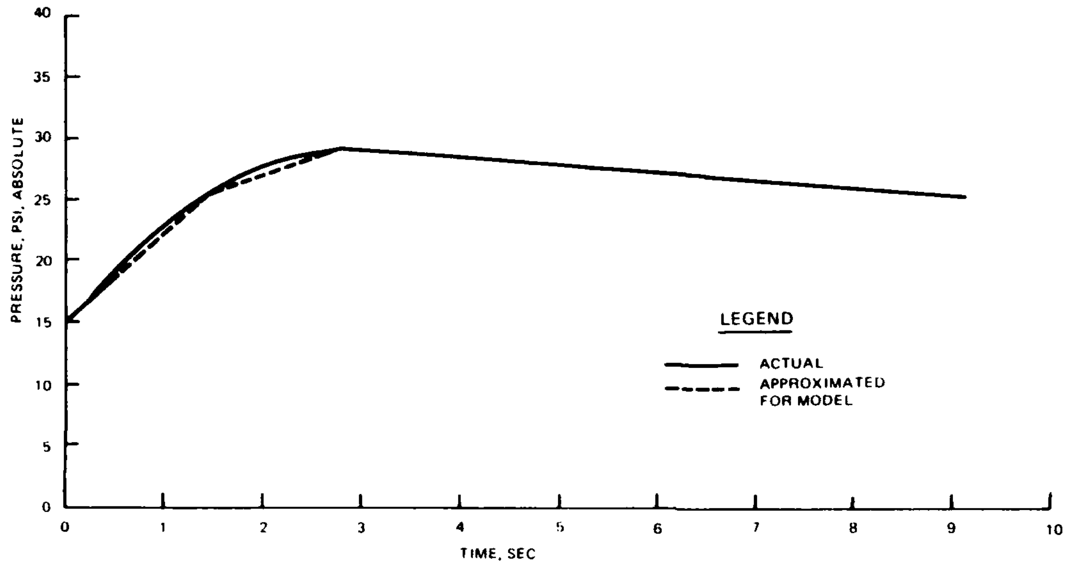


Figure 16. Pressure-time history for Clarks Hill

91. A numerical model was developed to track a water particle as it moves through the draft tube. It temporally steps through the pressure history of the draft tube with very small time intervals and solves Equation 19 for final DO deficits at each step, accounting for the impact of increased pressure on the deficit. In the model, the final deficit for the previous time step becomes the initial deficit for the current time step. In this manner, the initial DO deficit is "stepped" through the draft tube in finite increments. At each of these time steps an improvement of the release DO, due to venting, is achieved. This stepwise reaeration continues until the air bubbles reach the surface in the tailrace.

92. The EDM (Equation 10) is then applied to the DO deficit for

the prediction of final release DO concentration. The combination of the pressure-time model (Equation 19), the numerical (computer) technique of stepping through the pressure-time history, and application of the EDM comprises the numerical model of turbine reaeration called VENTING. A simplified schematic of the computer model is shown in Figure 17.

93. To use VENTING, an estimate of a gas transfer coefficient, which is the unknown quantity in Equation 19, must be developed. A least squares regression analysis of part of the available observed DO and Q-air/Q-water ratio and the temperature correction (Churchhill, Elmore, and Buckingham 1962; Tsivoglou and Wallace 1972) relationship

$$a_T = a_{20}(1.024)^{(T-20)} \tag{21}$$

where a_T and a_{20} represent gas transfer coefficients for water temperatures of T (ambient) and 20° C, respectively, were used to estimate the gas transfer coefficient. However, in performing this analysis, it was necessary to include the turbulent reaeration model (Equation 15) and the effect of the pressure-time history on the deficit ratio. Thus, determining the estimate of a_{20} was an iterative process that used the numerical model VENTING.

94. Regression analysis with the data taken at Clarks Hill in 1982 resulted in an estimate of $a_{20} = 0.33/\text{sec}$. Figure 18 shows the release DO predicted with the model VENTING versus the observed release DO concentrations for the 1982 field studies. The standard error of estimate for these data was 0.5 mg/ℓ. The maximum prediction error was -1.1 mg/ℓ. Predictions were then made with the model for the 1981 data. These data were not used in the model development. Figure 19 shows the predicted versus observed release DO concentrations for the 1981 field data (also shown in Tables A8-A9). The standard error of estimate for these predictions was 0.3 mg/ℓ. The maximum prediction error was -0.8 mg/ℓ. These results indicate that the reaeration processes at work in the turbine venting can be described quite accurately for the Clarks Hill project.

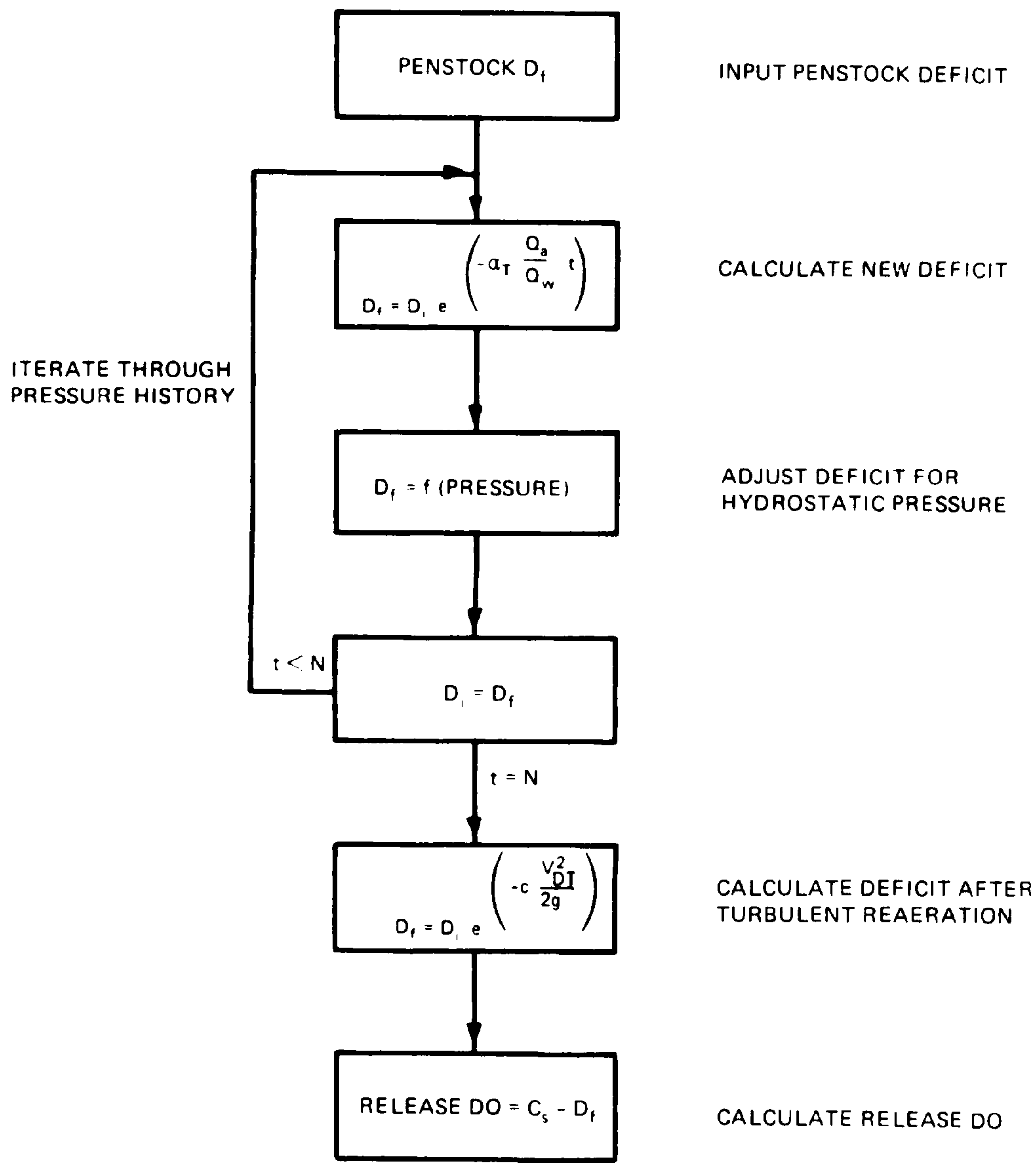


Figure 17. Simplified schematic of the reaeration computations

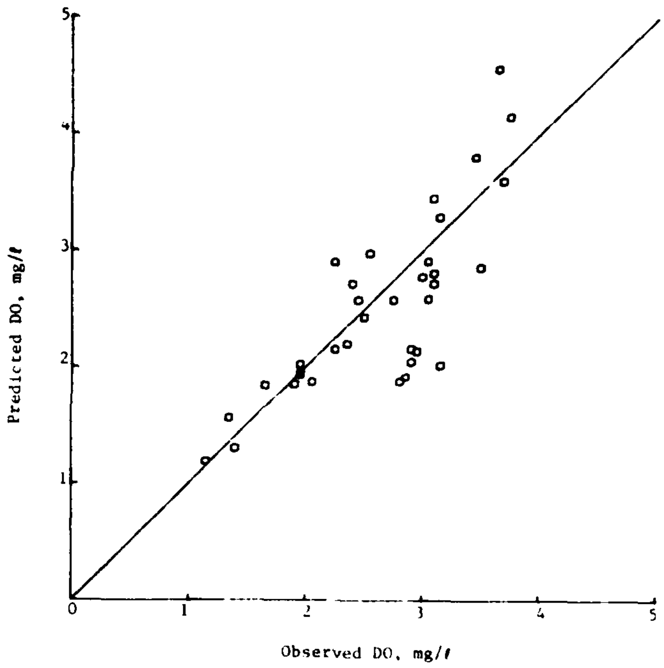


Figure 18. Predicted versus observed DO for the 1982 study

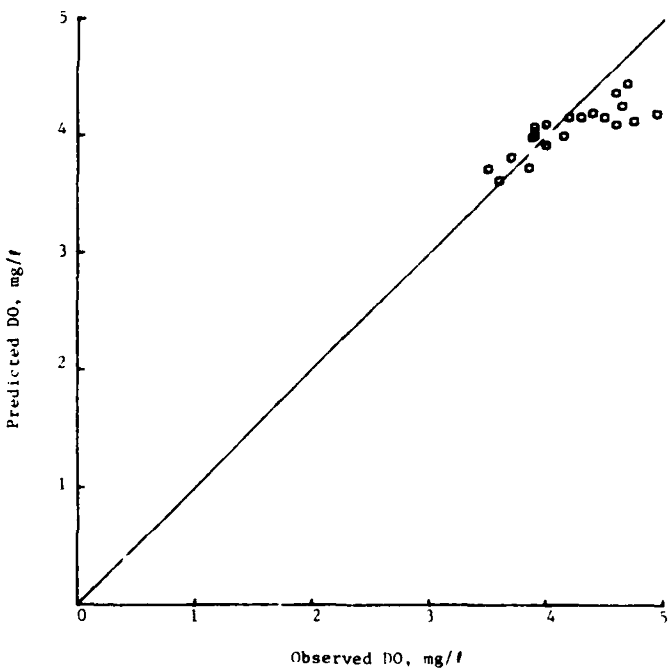


Figure 19. Predicted versus observed DO for the 1981 study

Model Application

95. The numerical model, coupled with the relationship between efficiency loss and Q-air/Q-water shown in Figures 11 and 12, allows us to estimate the costs for improving release DO with turbine venting. For this example, two Q-air/Q-water ratios (1.5 and 3.5 percent), four penstock (upstream) DO concentrations, and two turbine discharges (3,000 and 4,500 cfs) will be used to show the utility of the numerical model and efficiency loss relationships. The pressure-time history of the Clarks Hill project will also be used as input to the model. A complete listing of the model and the input data to VENTING for this example is given in Appendixes C and D. Assuming a water temperature of 28° C, Table 3 displays what could be expected at Clarks Hill for release DO (since the hydraulic data are Clarks Hill data) with turbine venting for the data outlined above.

Table 3

Predicted Release DO, mg/ℓ

(Water Temperature, 28° C; C_s = 8.0 mg/ℓ)

Penstock DO mg/ℓ	Q-Water: 3,000 cfs		Q-Water: 4,500 cfs	
	Q_A/Q_W* = 1.5%	Q_A/Q_W = 3.5%	Q_A/Q_W = 1.5%	Q_A/Q_W = 3.5%
0.1	1.9	3.4	2.1	3.3
0.5	2.2	3.7	2.4	3.5
1.0	2.6	4.1	2.8	3.9
4.0	5.1	6.2	5.2	6.0

* Q_A/Q_W = air flow-to-water flow ratio.

96. The improvement in release DO with the 1.5-percent air flow is somewhat limited compared to 3.5-percent air flow. The largest DO uptake experienced with the 1.5-percent air flow was 2.0 mg/ℓ, whereas the maximum DO uptake for the 3.5-percent air flow was 3.3 mg/ℓ. Significant improvement for release DO can be achieved with the higher air flow rate. However, a price, in terms of greater efficiency loss (a loss of power production) and thereby a loss in revenue, must be paid.

97. From Figures 11 and 12, the efficiency loss at a Q-air/-Q-water ratio of 1.5 percent would be about 1.0 percent; for a Q-air/-Q-water ratio of 3.5 percent, the efficiency loss would be approximately 2.5 percent. These losses are a result of the air that was introduced into the flow. Thus, if deflectors were used to enhance the air flow, an additional loss would have to be included to accurately assess the economics of such a system. By considering plant size and operation, this efficiency loss can be converted to power loss.

98. For the purpose of this example, the effect of the efficiency loss was computed in terms of power loss using

$$P_L = 1.356(10^{-6})\ e_L Q \gamma H \tag{22}$$

where

P_L = power loss, MW

$1.356(10^{-6})$ = constant for conversion of ft-lb/sec to MW

e_L = efficiency loss, percent

H = gross head, assumed (for example, 146 ft)

99. *Using Equation 22 and* the 1.0- and 2.5-percent efficiency losses, power losses due to venting (losses due to hub deflectors not included) are displayed in Table 4.

Table 4

Power Loss Due to Venting, MW

Efficiency Los %	Discharge, cfs 3,000	Discharge, cfs 4,500
1.0	0.37	0.56
2.5	0.93	1.39

100. To determine the costs of these power losses, the duration of turbine operation must be included. For every hour that the turbine operates at 4,500 cfs, about 1.4 MWhr of energy would be lost due to venting air into the turbine at a rate of 3.5 percent of the water

flow rate. The unit price of megawatt-hours could then be used to compute the actual revenue losses. Additional information on cost is available in Lewis and Bohac (1984).

PART VI: SUMMARY AND CONCLUSIONS

101. Hydropower is one of the cleanest domestic sources of energy. Its use has been expanding and will inevitably continue to expand as nonrenewable sources of energy (fossil fuel) diminish or become more expensive. Even though hydropower possesses many very attractive attributes, there are some potential adverse impacts that can affect the quality of water both in the reservoir and downstream. The most frequently cited potential adverse impact is the release of water with a low DO concentration. This may occur if the reservoir is thermally or chemically stratified.

102. Naturally occurring chemical and biological processes reduce the level of DO in the lower levels of the lake and, because of the thermal stratification (density stratification), this oxygen cannot be replenished by reaeration at the reservoir's surface. Hence, the lower levels of the reservoir may become low in DO or even anoxic. As a result, the releases from a hydropower project (since hydropower projects usually withdraw water from deep in the upstream pool) can be very low in DO. With these conditions, the quality of water released from the hydropower project in some instances may be unacceptable relative to objectives for the downstream environment unless measures are undertaken to improve the DO in the release water.

103. Several techniques to improve the quality of turbine releases are available. These techniques are of three general categories: forebay systems, tailwater systems, and in-structure systems. The appropriate reaeration alternative must be determined on a case-by-case basis. Applicability of tailwater systems appears limited because of the usually large discharge rate of hydropower projects. Many of the forebay systems partially or totally break up the thermal stratification in the reservoir. This may be unacceptable due to a possible change in the release temperature or mixing of the distinct water quality layers within the reservoir. Hypolimnetic aeration or oxygenation systems, if properly designed and operated, could provide improved release DO without significantly affecting the reservoir's

stratification patterns. However, the potential for nitrogen supersaturation exists for the aeration systems. The addition or retrofit of selective withdrawal facilities to a project can provide the flexibility to improve the release DO; however, release temperature is usually increased, which may be an unacceptable consequence. Further, the addition of a selective withdrawal system to accommodate the magnitude of hydropower discharges would, in most cases, be very expensive.

104. Of all the alternatives, the in-structure techniques, which usually involve the injection or aspiration of air or oxygen into the release flow at different locations in the structure, are the most attractive for release DO improvement. In particular, for CE projects, turbine venting appears the most applicable. Briefly, the advantages of a turbine venting system are:

a. Normally, all project releases pass through the turbine, thereby allowing the entire project outflow to be enhanced at one location.

b. In some cases, no mechanical means or external power sources are required.

c. Turbine venting usually has no detrimental aesthetic impact on the reservoir or tail race.

d. Costs for a venting system (capital and operational) are usually less than for other alternatives.

105. There are, however, some disadvantages and limitations for a turbine venting system, including:

a. Generally, reductions in turbine efficiency and capacity have been observed at test sites.

b. The amount of reaeration may be limited, possibly as a result of the hydraulics of the release system of a hydropower project.

106. Several alternatives exist with regard to the method by which a turbine is vented. For Francis turbines, low pressure in the draft tube at low operating levels (low wicket gate settings) causes air to be aspirated into the flow. Ordinarily, the vacuum-breaker system (pipe and valve network designed to vent the turbine to alleviate the low pressure and prevent cavitation) conducts the air flow into the

turbine. However, the capacity of the vacuum-breaker system is limited. Significant improvement of the venting capability (increased air flow) can be achieved by installing a bell-mouth intake on the air supply to the turbine, thereby avoiding the large aerodynamic losses of air flow through the vacuum-breaker system. Even more air flow can be vented into the turbine if a compressor is employed for forced-air injection (although in the study reported herein, the compressor was too small for significant improvements). Very large flow rates of air may be introduced to the turbine flow if deflector plates are installed on the hub of the turbine upstream of the venting ports.

107. The study of turbine venting at the Clarks Hill hydropower facility was designed to improve our understanding of the reaeration process during turbine venting and to provide guidance on the application of this technique. The results of the study indicate that turbine venting can be an excellent method of improving concentration of DO in releases from hydropower projects. The following is a general list of conclusions resulting from the turbine venting study at the Clarks Hill project:

a. Significant reaeration and improvement of release DO can be achieved by employing turbine venting. In terms of the oxygen deficit, this study indicated that about 30 percent of the upstream deficit could be satisfied at Clarks Hill Reservoir.

b. Two processes were identified with the uptake of oxygen in hydropower releases: (1) turbulent reaeration (oxygen transfer from the atmosphere) in the tailrace just downstream of the draft tube outlet and (2) aspiration or injection of air at the turbine, resulting in DO transfer to the water from the air bubbles as they travel with the release through the draft tube. From this study, the turbulent reaeration in the tailrace accounted for up to 6 percent of the reduction in the DO deficit.

c. The effectiveness of the turbine venting systems studied to improve the release DO was highly dependent on the air flow rate relative to the turbine discharge rate. A reduction in the upstream DO deficit of about 30 percent was achieved with an air flow rate of about 3 percent of the turbine discharge rate. Less reaeration was observed with lower air flow rates.

d. The cost of achieving reductions in the DO deficit was reflected in reduced turbine operating efficiency. For the example given above, an air flow rate of 3 percent of turbine

discharge resulted in an efficiency reduction of approximately 2 percent. The reduction is due to the introduction of air to the turbine. If deflector plates are employed to enhance air flow, an additional efficiency loss would have to be included. This effect on turbine efficiency was an actual loss of generating potential; hence, it can be assigned an actual cost.

e. At Clarks Hill, for the turbine without deflector plates, a slight increase in turbine efficiency was observed for very small air flow-to-water flow ratios (less than 1 percent). This slight improvement in efficiency was probably due to a smoother running turbine. However, the impact on the release DO for these small air flow-to-water flow ratios was minimal. This slight increase in efficiency could be used to offset all or part of the loss in efficiency that occurs when venting for DO enhancement. During periods of high DO release, e.g., late fall, winter, and spring, venting the turbine with small air volumes could improve power production up to 0.75 percent and partially offset the power loss during the summer months.

f. To determine if turbine venting is a tractable alternative, a technique to evaluate the potential improvement in DO is required. Based on the data collected in this study, a numerical model was developed as a predictive tool for estimating the effects of turbine venting on reducing DO deficits. The computer model includes in its formulation the reaeration that occurs in the tailrace due to turbulence and the gas transfer due to the transport of air bubbles through the draft tube. The mathematical description of the former process was based on the premise that reaeration in the tailrace was a function of the energy that was dissipated. It was approximated by the kinetic energy (velocity head) of the turbine discharge as the flow exits the draft tube. The latter gas transfer process was described by using a pressure-time history concept to account for the effect of increased hydrostatic pressure (which changes the thermodynamic state) on the air bubbles as they move with the turbine discharge through the draft tube. The combination of these two process descriptions resulted in the numerical model VENTING, which will predict the oxygen improvement due to turbine venting.

108. It must be pointed out that these data represent the observed response of turbines at the Clarks Hill project. It is reasonable to expect similar responses from facilities of similar size, geometry, and equipment. However, it must be recognized that for significantly different projects, the applicability of these predictions may be limited.

REFERENCES

Bohac, C. E., Boyd, J. E., Harshbarger, E. D., and Lewis, A. R. 1983. "Techniques for Reaeration of Hydropower Release," Technical Report E-83-5, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Buck, C. L., Miller, D. E., and Sheppard, A. R. 1980 (Aug). "Prediction of Oxygen Uptake Capabilities in Hydroelectric Turbines Utilizing Draft Tube Aeration Systems," Environmental and Research Services Section, Alabama Power Company, Birmingham, Ala.

Churchill, M. A., Elmore, H. L., and Buckingham, R. A. 1962 (Jul). "The Prediction of Stream Reaeration Rates," Journal of the Sanitary Engineering Division, Proceedings of the American Society of Civil Engineers, VOL SA4.

Dortch, M. S. 1979. "Artificial Destratification of Reservoirs," Technical Report E-79-1, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Dortch, M. S., and Holland, J. P. 1980. "Methods of Total Lake Destratification, Proceedings of the Symposium on Surface Water Impoundments, 2-5 June 1980, Minneapolis, Minn., sponsored by the American Society of Civil Engineers, New York.

Dortch, M. S., and Wilhelms, S. C. 1978. "Enhancement of Releases from a Stratified Impoundment by Localized Mixing, Okatibbee Lake, Mississippi," Miscellaneous Paper H-78-1, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Fast, A. W., and Hulquist, R. G. 1982. "Supersaturation of Nitrogen Gas Caused by Artificial Aeration in Reservoirs," Technical Report E-82-9, prepared by Limnological Associates, Kaneohe, Hawaii, for the US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Fast, A. E., and Lorenzen, M. W. 1976. "Synoptic Survey of Hypolimnetic Aeration," Journal of the Environmental Division, Proceedings of the American Society of Civil Engineers, Vol 102, p 1161.

Gameson, A. 1957. "Weirs and the Aeration of Rivers," Journal of the Institute of Water Engineers, London, England, Vol 11, No. 6 (Oct), p 477.

Garton, J. E., and Jarrell, F. R. 1976. "Demonstration of Water Quality Enhancement Through the Use of the Garton Pump," Supplement to Technical Completion Report C-5228, Oklahoma State University, Stillwater, Okla.

Garton, J. E., and Rice, C. E. 1974. "Low Energy Mechanical Methods of Reservoir Destratification," OWRRI Final Technical Completion Report A-028-OKLA, Oklahoma State University, Stillwater, Okla.

George, J. F., Dortch, M. S., and Tate, C. H., Jr. 1980. "Selective Withdrawal Riser for Sutton Dam, West Virginia," Technical Report HL-80-4, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Holland, J. P. 1984 "Parametric Investigation of Localized Mixing,"

Technical Report E-84-7, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Holland, J. P., and Dortch, M. S. 1984. "Design Guidance on Hydraulic Destratification," Enviromental and Water Quality Operational Studies Information Exchange Bulletin, Vol E-84-4 (Aug), US Army Engineer Waterways Experiment Stations, Vicksburg Miss.

Holland, J. P., and Tate, C. H., Jr. 1984. "Investigation and Discussion of Techniques for Hypolimnion Aeration/Oxygeneration," Technical Report E-84-10, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Lewis, A. L., and Bohac, C. E. 1984. "Costs of Reservoir Release Aeration," Tennessee Valley Authority, Chattanooga, Tenn.

Mauldin, G. V. 1982. "Turbine Venting at Clarks Hill Dam," Proceedings, US Army Engineer Water Quality Workshop; Attaining Water Quality Goals Through Water Management Procedures, Dallas, Tex.

Maynord, S. T., and Tate, C. H., Jr. 1983. "Model Study of Cave Run Reservoir Outlet Works," Draft Technical Report, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Merritt, D. H., and Leggett, D. 1981. "Dissolved Nitrogen Measurements at Clarks Hill Reservoir, Georgia-South Carolina," Office, Chief of Engineers, US Army, Washington, DC (NTIS, Springfield, Va.).

Pastorok, R. A., Lorenzen, M. W., and Ginn, T. L. 1982. "Environmental Aspects of Artificial Aeration and Oxygenation of Reservoirs: A Review of Theory, Techniques, and Experiences," Technical Report E-82-3, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Pfau, A. 1948. "Hydraulic Turbine Handbook: Modern Hydraulic Prime Movers," Allis Chalmers Manufacturing Company.

Raney, D. C. 1973 (Sep). "Experimental Measurement of Base Pressure Coefficients for Deflector Plates with Air Injected into the Wake Region," BER Report, University of Alabama, Tuscaloosa, Ala.

Raney, D. C. 1975 (Jun). "Water Tunnel Modeling of Turbine Aspiration Systems," BER Report 870-30, University of Alabama, Tuscaloosa, Ala.

Raney, D. C., and Arnold, T. G. 1973. "Dissolved Oxygen Improvement by Hydroelectric Turbine Aspiration," Journal of the Power Division, American Society of Civil Engineers.

Schroeder, E. D. 1977. Water and Wastewater Treatment, McGraw-Hill, New York.

Speece, R. E. 1975a (Feb). "Final Feasibility Report, Oxygen Restoration to Waters Released from Clarks Hill Reservoir," US Army Engineer District, Savannah, Savannah, Ga.

Speece, R. E. 1975b (Oct). "Oxygenation of Clarks Hill Reservoir Discharges," Symposium on Reaeration Research, American Society of Civil Engineers, Gatlinburg, Tenn.

Speece, R. E., et al. 1977 (Mar). "Oxygenation Tests at Clarks Hill Lake - Final Report," US Army Engineer District, Savannah, Savannah, Ga.

Tennessee Valley Authority. 1981 (Dec). "Improving Reservoir Releases," Report No. TVA/ONR/WR-82/6, Knoxville, Tenn.

Tennessee Valley Authority. 1982. "Evaluation of Turbine Venting Systems at Norris Dam," Report No. WR28-1-2-102, Norris, Tenn.

Tennessee Valley Authority. 1984. "Impact Bulletin," TVA/ONRED/SFO-85/2, Vol 7, No. 4, Chattanooga, Tenn.

Tsivoglou, E. C., and Wallace, J. R. 1972 (Oct). "Characterization of Stream Reaeration Capacity," EPA-R3-72-012, Office of Research and Monitoring, US Environmental Protection Agency, Washington, DC. US Army Engineer District, Savannah. 1969. "Allatoona Reservoir Interim Report No. 1," Savannah, Ga.

Tsivoglou, E. C., and Wallace, J. R. 1981a. "Richard B. Russell Dam and Lake, Design Memorandum No. 3, General Design Memorandum Supplement No. 2, Water Quality Control System," Savannah, Ga.

Tsivoglou, E. C., and Wallace, J. R. 1981b. "Richard B. Russell Dam and Lake, Design Memorandum No. 35, Oxygenation Distribution and Diffusion System," Savannah, Ga.

Tsivoglou, E. C., and Wallace, J. R. 1982. "Richard B. Russell Dam and Lake, Design Memorandum No. 35, Supplement No. 1, Oxygenation Production and Storage Facilities,
" Savannah, Ga.

Wilhelms, S. C. 1983. "Hydropower Additions to Flood Control Projects," Hydraulics Laboratory (12 Sep), US Army Engineer Waterways Experiment Station, Vicksburg Miss.

Wilhelms, S. C. 1984. "Measurements of Dissolved Gases at Corps of Engineers Projects," Technical Report E-84-6, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Wilhelms, S. C. 1985. "Selective Withdrawal: Basic Concepts," Proceedings, CE Workshop on Selective Withdrawal Intake Structure Design and Operation, June 24-27, 1985, San Francisco, Calif., (available from US Army Engineer Waterways Experiment Station, Vicksburg, Miss.).

Wilhelms, S. C., and Smith, D. R. 1981. "Reaeration Through Gated-Conduit Outlet Works," Technical Report E-81-5, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

APPENDIX A: TABULATED FIELD STUDY DATA

Table A1

Data from Unit 2, No Deflectors, 0% Air, Vacuum Breaker, 1982 Study

Wicket Gate (%)	Gross Head (ft)	Discharge (cfs)	Power Output (MW)	Air Flow (cfs)	Penstock D.O. (mg/l)	Downstream D.O. (mg/l)	Water Temperature (C)	Head Cover Vacuum (ft water)	TDGP (mm Hg)	Barometric Pressure (mm Hg)
30	144.53	2069	19.69		0.50	0.85	17.47	20.8	645	750
40	144.44	2701	28.30		0.40	0.80	17.47	16.8	642	750
50	144.13	3322	35.43		0.70	0.75	17.30	12.8	634	750
55	144.27	3599	38.60		0.65	0.75	17.30	11.8	637	750
60	144.17	3845	41.48		0.65	0.80	17.30	10.3	636	750
65	144.27	4062	43.86		0.60	0.93	17.30	8.8	639	750
70	144.44	4292	45.71		0.35	1.25	17.47	9.3	647	750
70	144.20	4278	45.53		0.60	1.07	17.30	7.3	646	750
75	144.22	4522	47.45		0.60	1.18	17.30	5.3	648	750
80	144.47	4691	48.94		0.40	1.45	17.47	6.8	652	750
80	144.11	4683	48.80		0.65	1.38	17.30	5.3	655	750
85	144.15	4817	49.76		0.30	1.55	17.47	2.3	651	750

Table A2

Data from Unit 2, No Deflectors, 100% Air,

Vacuum Breaker, 1982 Study

Wicket Gate (%)	Gross Head (ft)	Discharge (cfs)	Power Output (MW)	Air Flow (cfs)	Penstock D.O. (mg/l)	Downstream D.O. (mg/l)	Water Temperature (C)	Head Cover Vacuum (ft water)	TDGP (mm Hg)	Barometric Pressure (mm Hg)
30	144.28	1988	19.44	53.2	0.50	3.10	17.47	8.3	761	750
40	144.40	2648	27.07	52.5	0.45	2.75	17.47	10.3	732	750
50	144.40	3301	35.08	42.1	0.35	2.05	17.47	9.8	NA	750
55	144.24	3545	38.45	30.5	0.65	1.65	17.30	6.8	682	750
60	144.20	3824	41.27	14.9	0.65	1.35	17.30	6.3	662	750

Table A3

Data from Unit 2, No Deflectors, 100% Air,

Bell Mouth, 1982 Study

Wicket Gate (%)	Gross Head (ft)	Discharge (cfs)	Power Output (MW)	Air Flow (cfs)	Penstock D.O. (mg/l)	Downstream D.O. (mg/l)	Water Temperature (C)	Head Cover Vacuum (ft water)	TDGP (mm Hg)	Barometric Pressure (mm Hg)
40	144.22	2578	26.27	97.7	0.67	3.75	17.66	8.8	804	749
45	144.26	2986	30.31	66.3	0.28	3.05	17.66	7.8	772	749
50	144.22	3268	34.35	58.6	0.28	2.35	17.66	7.8	731	749
55	144.21	3581	38.38	50.1	0.30	1.95	17.66	7.8	703	749
60	144.20	3845	41.48	18.1	0.30	1.40	17.66	7.8	675	749
65	144.22	4087	43.84	9.3	0.30	1.15	17.66	7.3	663	749

Table A4

Data from Unit 2, No Deflectors, 100% Air, Blower,

1982 Study

Wicket Gate (%)	Gross Head (ft)	Discharge (cfs)	Power Output (MW)	Air Flow (cfs)	Penstock D.O. (mg/l)	Downstream D.O. (mg/l)	Water Temperature (C)	Head Cover Vacuum (ft water)	TDGP (mm Hg)	Barometric Pressure (mm Hg)
45	144.15	2934	30.04	90.6	0.77	3.70	17.50	5.3	787	745
50	144.15	3263	34.10	72.1	0.75	3.05	17.50	5.3	786	745
55	144.12	3581	38.09	59.2	0.65	2.50	17.50	5.3	786	745
60	144.17	3845	41.36	36.7	0.62	1.95	17.50	4.8	783	745
65	144.25	4108	43.96	ERATIC	0.62	N/A	17.50	4.8	N/A	745
70	144.17	4271	45.70	ERATIC	0.75	1.70	17.50	4.3	780	745

Table A5

Data from Unit 4, Deflectors, 0% Air,

Vacuum Breaker, 1982 Study

Wicket Gate (%)	Gross Head (ft)	Discharge (cfs)	Power Output (MW)	Air Flow (cfs)	Penstock D.O. (mg/l)	Downstream D.O. (mg/l)	Water Temperature (C)	Head Cover Vacuum (ft water)	TDGP (mm Hg)	Barometric Pressure (mm Hg)
40	144.14	2719	28.50		0.55	1.10	17.03	17.0	641	748
45	144.09	3053	32.22		0.45	0.85	17.32	14.2	647	747
50	144.23	3330	35.67		0.45	1.40	17.03	12.5	654	748
50	144.17	3341	35.88		0.44	0.85	17.32	14.0	655	747
55	144.28	3646	39.47		0.40	1.30	17.03	12.0	649	748
55	144.10	3634	39.41		0.40	0.80	17.22	14.0	649	747
60	144.31	3875	41.95		0.40	0.85	17.30	14.0	640	750
60	144.19	3861	42.15		0.40	0.80	17.22	15.0	647	747
65	144.32	4137	44.47		0.35	1.00	17.30	14.0	650	750
70	144.23	4309	46.06		0.35	1.75	17.03	12.5	660	748
75	144.23	4515	47.87		0.40	1.80	17.03	13.0	662	748
80	143.99	4712	49.19		0.45	1.90	17.03	17.0	660	748
80	144.18	4735	49.35		0.45	1.15	17.22	18.0	653	747
85	144.19	4862	50.41		0.45	1.35	17.22	19.5	666	747

Table A6

Data from Unit 4, Deflectors, 100% Air,

Vacuum Breaker, 1982 Study

Wicket Gate (%)	Gross Head (ft)	Discharge (cfs)	Power Output (MW)	Air Flow (cfs)	Penstock D.O. (mg/l)	Downstream D.O. (mg/l)	Water Temperature (C)	Head Cover Vacuum (ft water)	TDGP (mm Hg)	Barometric Pressure (mm Hg)
40	144.22	2675	27.43	60.0	0.55	3.50	17.03	9.5	728	748
45	144.12	2990	31.46	59.3	0.48	2.25	17.32	8.5	706	747
50	144.28	3310	34.95	57.4	0.45	2.95	17.03	5.0	704	748
55	144.31	3611	38.77	57.1	0.40	2.90	17.03	8.0	702	748
60	144.31	3854	41.45	52.9	0.38	1.95	17.30	7.0	692	750
65	144.33	4103	44.07	44.8	0.35	1.90	17.30	5.5	692	750
70	144.25	4300	45.81	43.3	0.40	2.80	17.03	6.5	698	748
75	144.27	4550	47.65	44.6	0.40	2.85	17.03	7.0	702	748
80	144.09	4704	49.00	45.4	0.50	2.90	17.03	4.5	701	748
85	144.35	4913	49.92	47.1	0.40	3.15	17.03	6.5	705	746

Table A7

Data from Unit 4, Deflectors, 100% Air,

Bell Mouth, 1982 Study

Wicket Gate (%)	Gross Head (ft)	Discharge (cfs)	Power Output (MW)	Air Flow (cfs)	Penstock D.O. (mg/l)	Downstream D.O. (mg/l)	Water Temperature (C)	Head Cover Vacuum (ft water)	TDGP (mm Hg)	Barometric Pressure (mm Hg)
40	144.24	2656	26.48	115.3	0.66	3.65	17.60	6.5	792	745
45	144.23	2965	30.34	105.7	0.56	3.45	17.60	6.0	792	745
50	144.31	3256	34.07	97.7	0.54	3.15	17.60	6.0	792	745
55	144.26	3570	37.74	99.4	0.38	2.55	17.60	6.0	733	745
60	144.25	3823	41.13	102.6	0.38	2.25	17.56	6.0	733	745
65	144.20	4096	43.81	95.2	0.42	2.40	17.46	6.5	733	745
70	144.27	4321	45.81	90.8	0.40	2.45	17.50	6.5	731	745
75	144.28	4491	47.67	101.8	0.50	3.00	17.60	6.0	786	745
80	144.15	4720	48.88	97.7	0.52	3.10	17.60	6.0	784	745
85	144.32	4889	50.03	104.1	0.55	3.10	17.60	6.5	780	745

Table A8

Data from Unit 4, Deflectors, Vacuum-Breaker

Venting, 1981 Study

Wicket Gate (%)	Gross Head (ft)	Discharge (cfs)	Power Output (MW)	Air Flow (cfs)	Penstock D.O. (mg/l)	Downstream Observed D.O. (mg/l)	Downstream Predicted D.O. (mg/l)	Water Temperature (C)	Barometric Pressure (mm Hg)
50	136.11	3187	31.46	59.7	2.90	4.70	4.45	18.90	756
55	136.12	3511	35.19	61.1	2.90	4.60	4.37	18.90	756
55	136.20	3420	34.30	48.3	2.90	4.30	4.16	19.00	756
55	136.23	3431	34.51	39.0	2.90	4.15	4.00	19.00	756
55	136.03	3429	34.56	24.2	2.90	3.85	3.73	19.00	756
55	135.79	3437	34.91	18.3	2.90	3.60	3.62	19.00	756
60	136.10	3736	37.79	58.1	2.90	4.65	4.26	18.90	756
65	136.08	3951	39.63	53.2	2.90	4.50	4.16	19.10	756
70	134.35	4144	41.01	39.7	2.90	3.88	3.99	18.30	757
75	136.07	4378	43.20	49.2	2.90	4.60	4.10	19.00	756
80	134.38	4530	44.38	41.0	2.90	3.90	4.03	18.30	757
85	136.02	4747	46.01	50.6	2.90	4.75	4.13	19.00	756
90	134.38	4887	46.28	41.0	2.90	3.90	4.08	18.40	757
95	136.02	5046	47.42	53.4	2.90	4.95	4.19	19.00	756
100	134.82	5280	47.18	49.7	2.90	4.40	4.20	18.90	757
100	134.82	5160	47.13	47.0	2.90	4.20	4.16	18.90	757
100	134.82	5193	47.35	39.7	2.90	4.00	4.10	18.90	757
100	134.81	5190	47.65	29.0	2.90	3.90	4.00	18.90	757
100	134.79	5193	47.56	20.5	2.90	4.00	3.92	18.90	757
100	134.72	5193	47.30	10.3	2.90	3.70	3.82	18.90	757

Table A9

Data from Unit 4, Deflectors, 0% Air,

Vacuum Breaker, 1981 Study

Wicket Gate (%)	Gross Head (ft)	Discharge (cfs)	Power Output (MW)	Air Flow (cfs)	Penstock D.O. (mg/l)	Downstream Observed D.O. (mg/l)	Downstream Predicted D.O. (mg/l)	Water Temperature (C)	Barometric Pressure (mm Hg)
50	136.07	3219	32.21		2.90	3.45		18.90	756
55	136.06	3440	34.75		2.90	3.30		19.00	756
55	136.11	3541	35.72		2.90	3.40		18.90	756
60	136.00	3767	38.15		2.90	3.40		19.10	756
60	136.04	3774	38.43		2.90	3.40		18.80	756
65	136.07	3977	40.34		2.90	3.45		18.90	756
70	134.36	4165	41.28		2.90	3.10		18.30	757
75	136.03	4389	43.41		2.90	3.70		19.00	756
80	134.37	4413	44.38		2.90	3.30		18.30	757
85	136.02	4706	46.01		2.90	3.90		19.00	757
90	134.47	4925	46.17		2.90	3.30		18.40	757
95	136.01	5050	47.88		2.90	4.30		19.00	756
100	134.59	5193	47.53		2.90	3.50		18.50	756

APPENDIX B: GRAPHICAL PRESENTATION AND ANALYSIS OF FIELD DATA

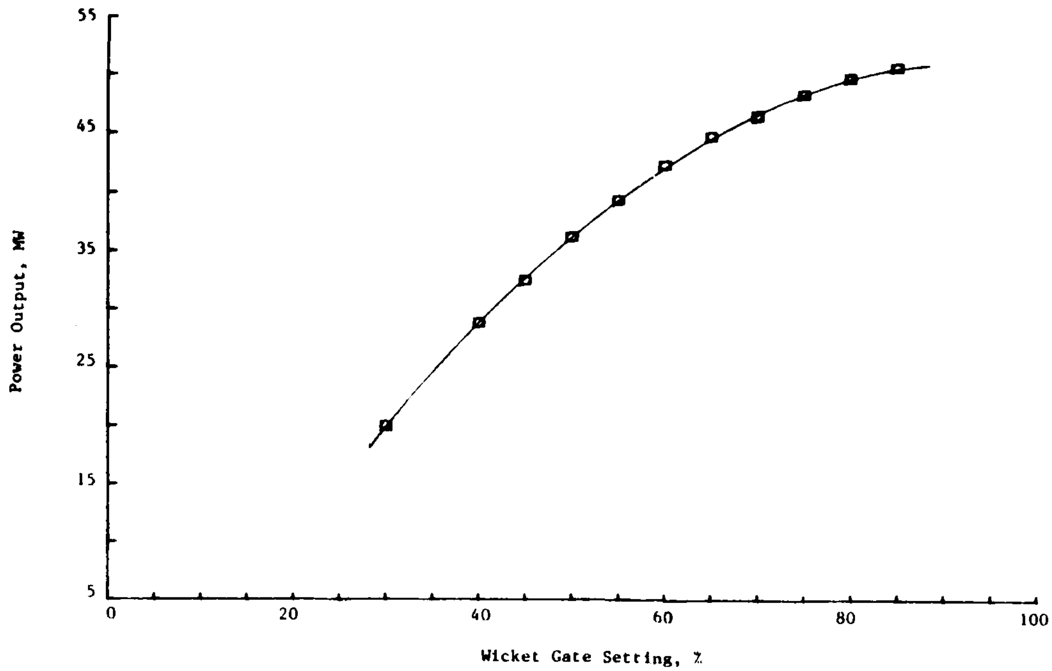


Figure B1. Power output versus wicket gate, power output adjusted to 146-ft gross head, Unit 2, no air flow

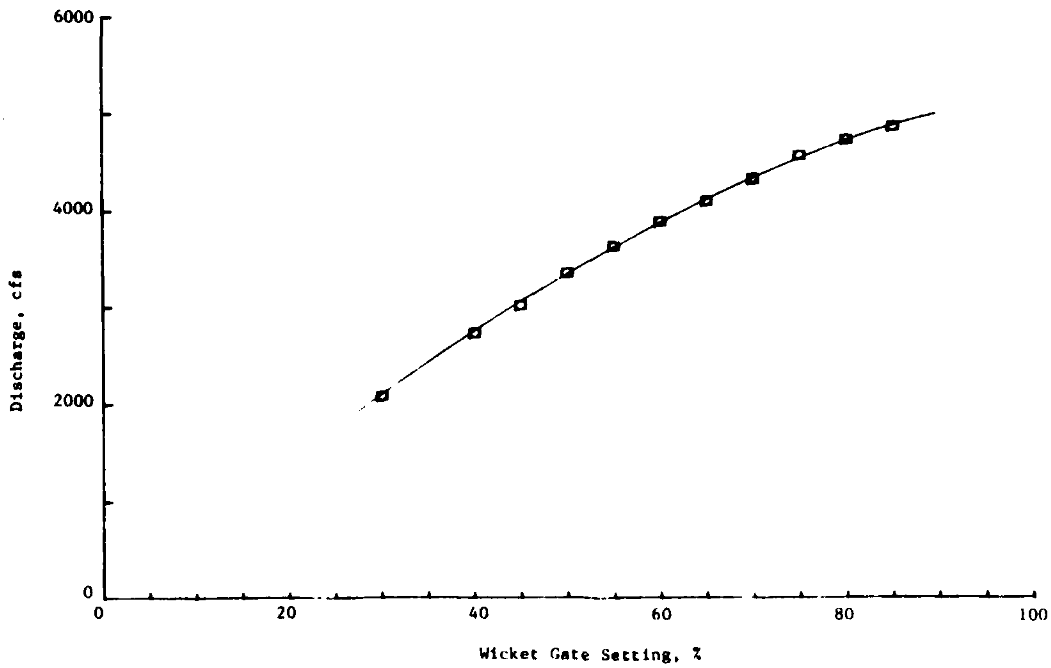


Figure B2. Discharge versus wicket gate, discharge adjusted to 146-ft gross head, Unit 2, no air flow

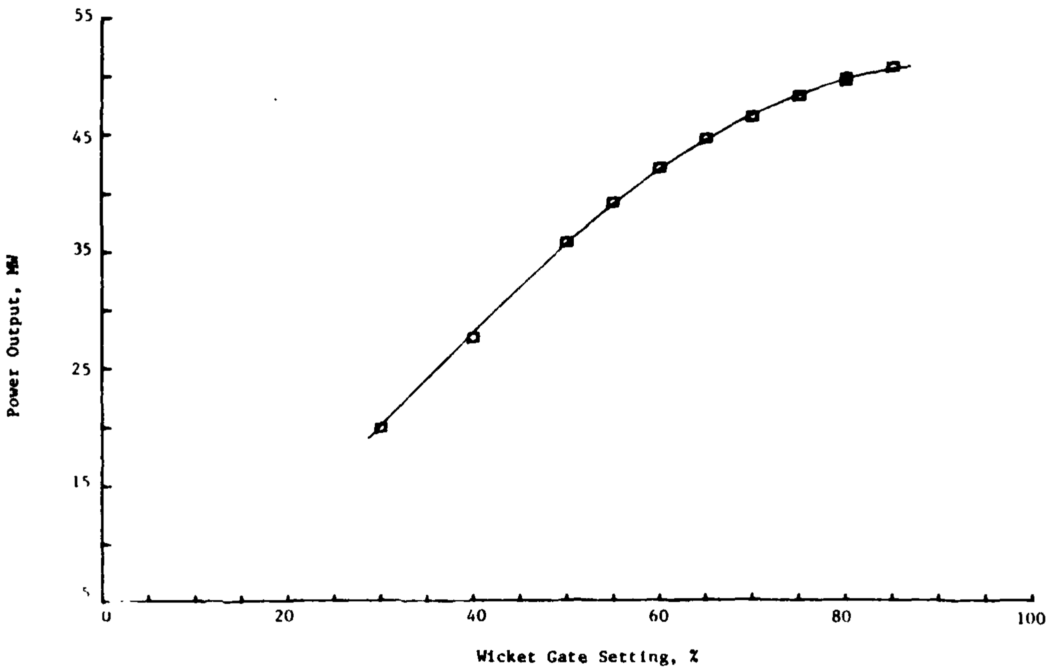


Figure B3. Power output versus wicket gate, power output adjusted to 146-ft gross head, Unit 2, vacuum breaker open

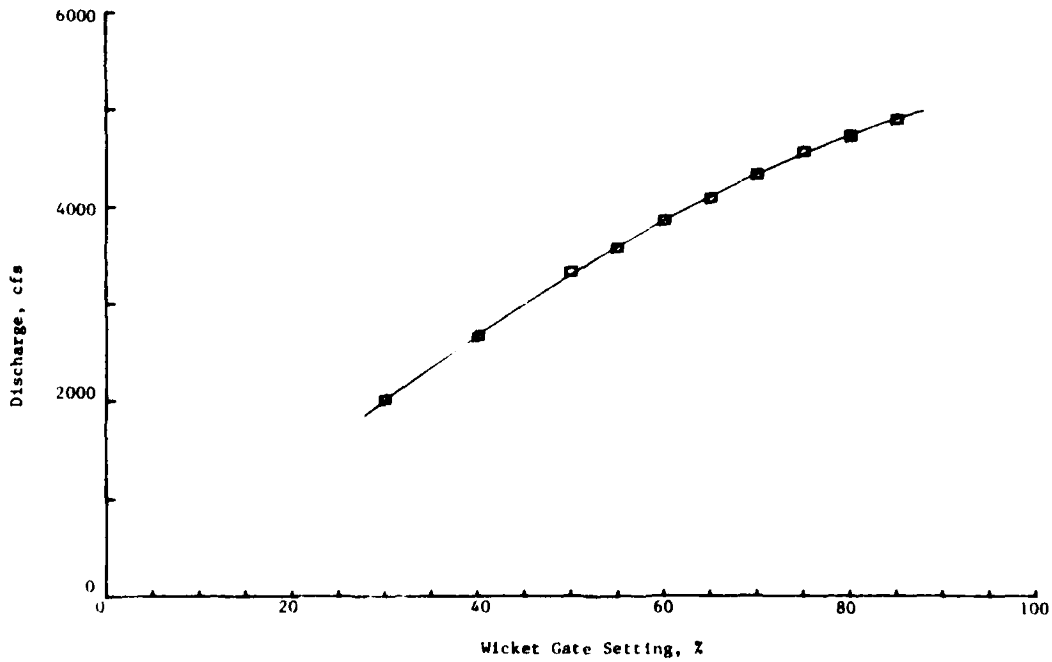


Figure B4. Discharge versus wicket gate, Discharge adjusted to 146-ft gross head, Unit 2, vacuum breaker open

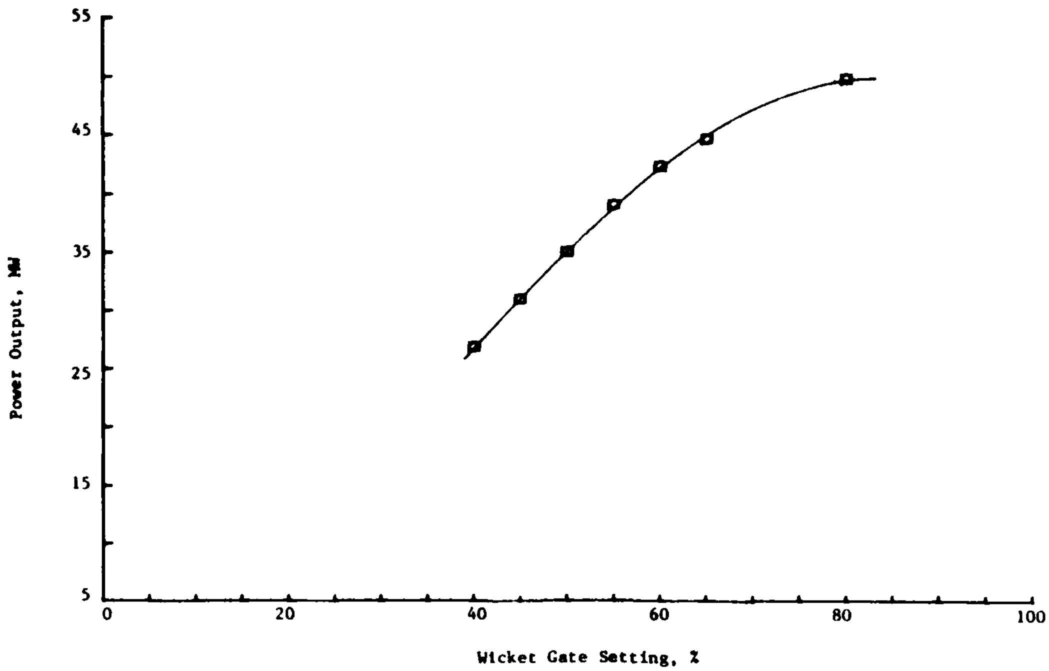


Figure B5. Power output versus wicket gate, power output adjusted to 146-ft gross head, Unit 2, bell-mouth intake air supply

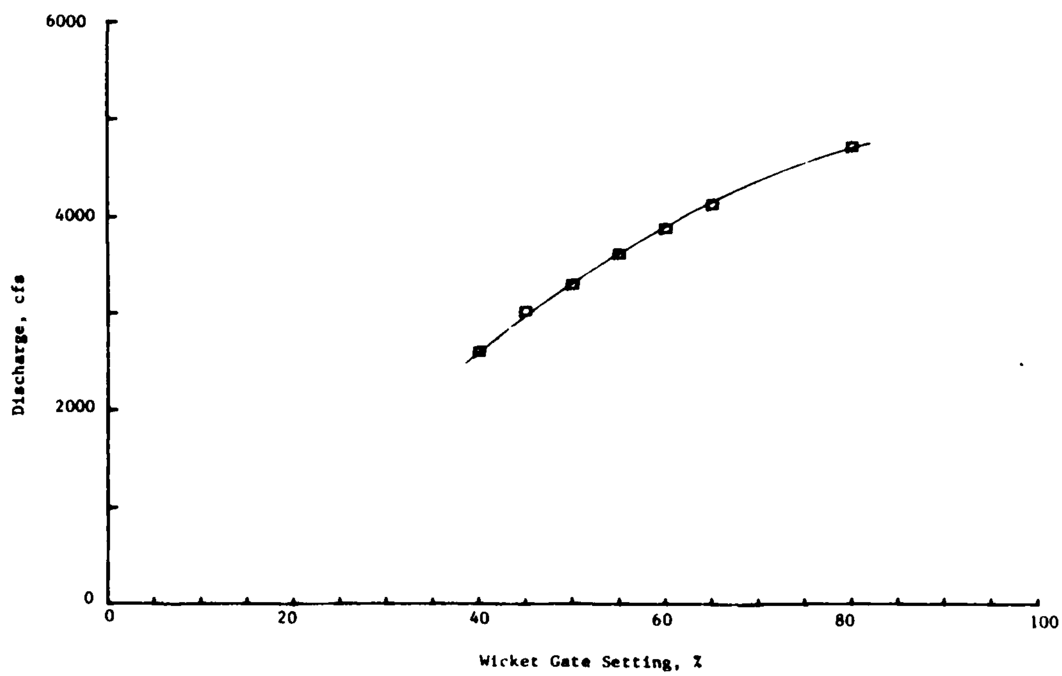


Figure B6. Discharge versus wicket gate, discharge adjusted to 146-ft gross head, Unit 2, bell-mouth intake air supply

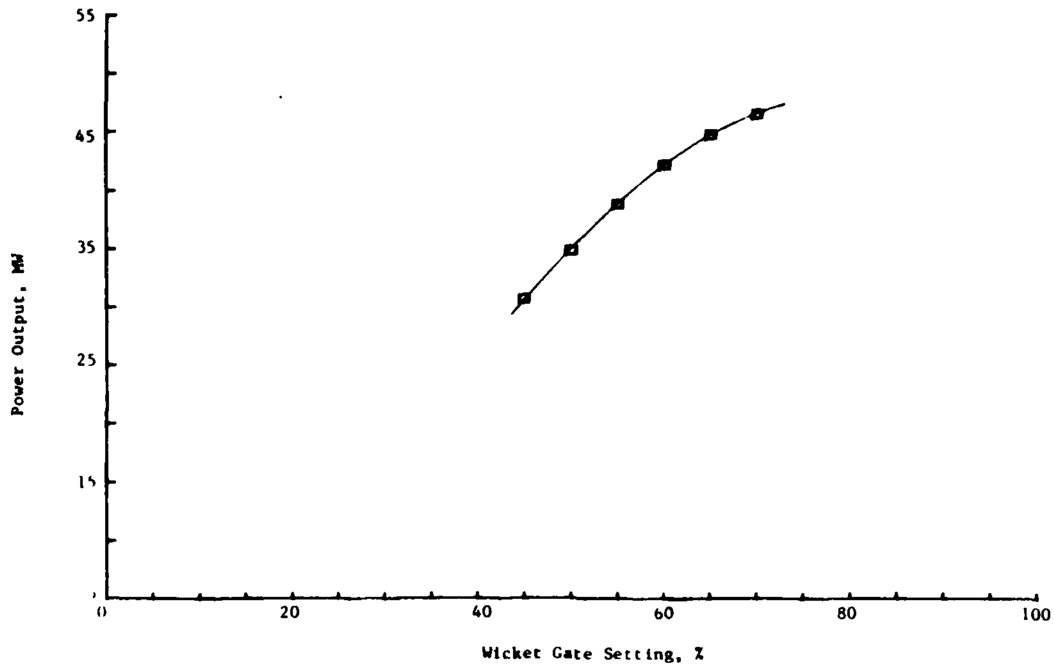


Figure B7. Power output versus wicket gate, power output adjusted to 146-ft gross head, Unit 2, blower-supplied air

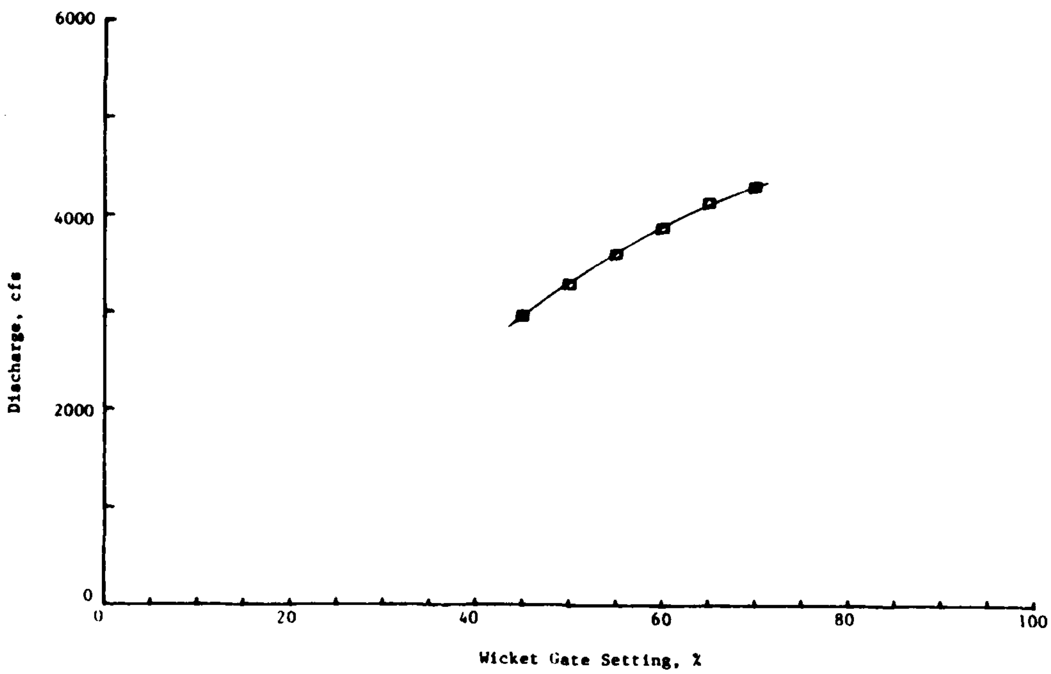


Figure B8. Discharge versus wicket gate, discharge adjusted to 146-ft gross head, Unit 2, blower-supplied air

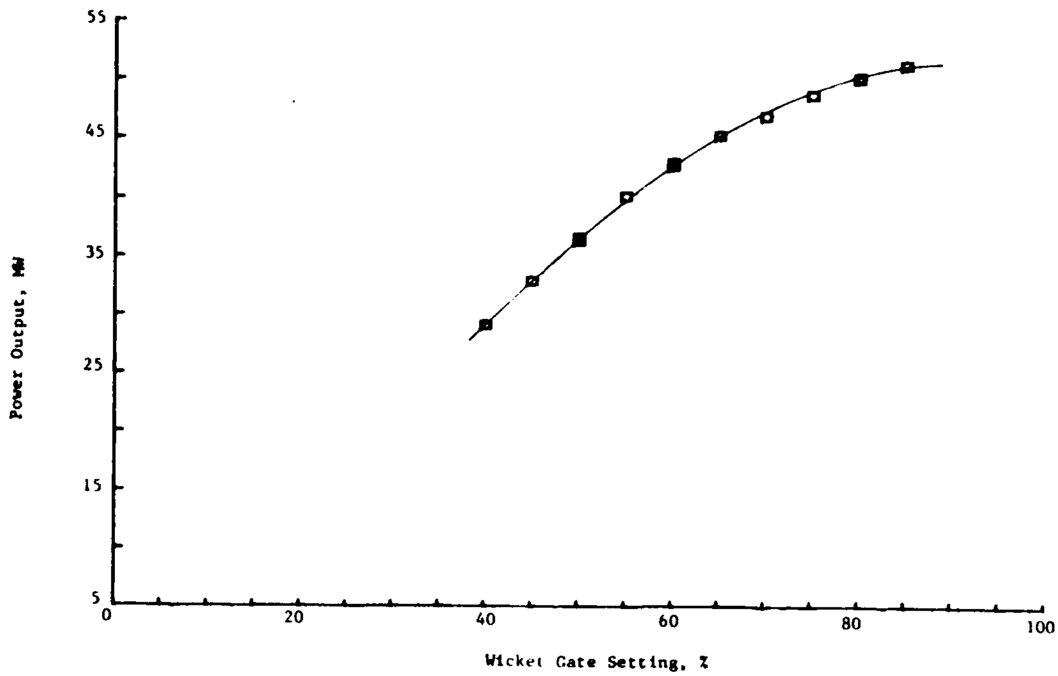


Figure B9. Power output versus wicket gate, power output adjusted to 146-ft gross head, Unit 4, no air flow

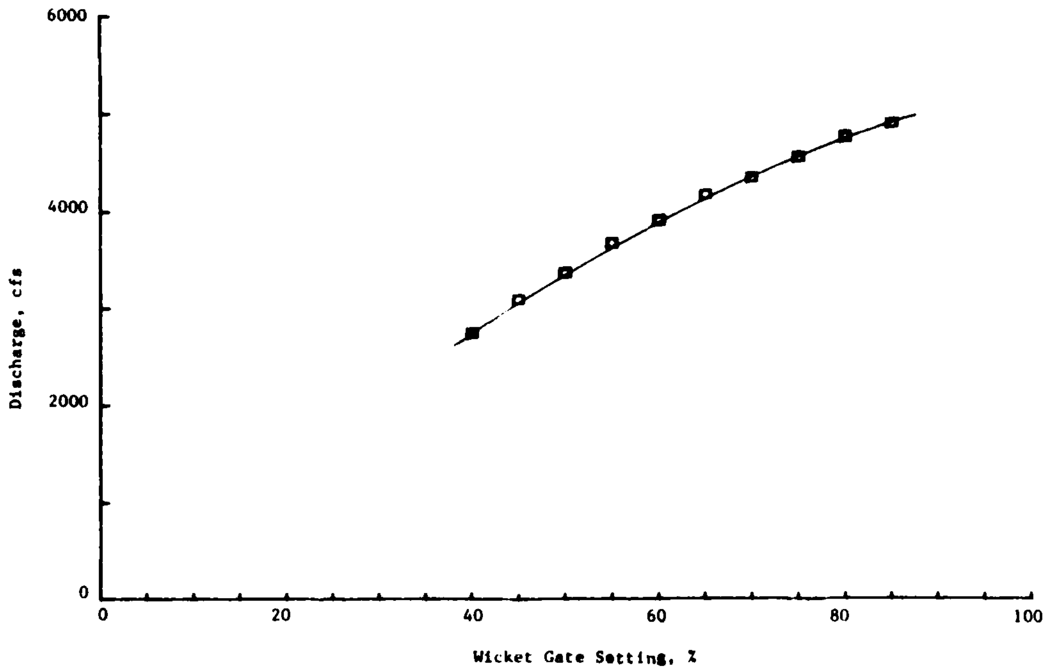


Figure B10. Discharge versus wicket gate, discharge adjusted to 146-ft gross head, Unit 4, no air flow

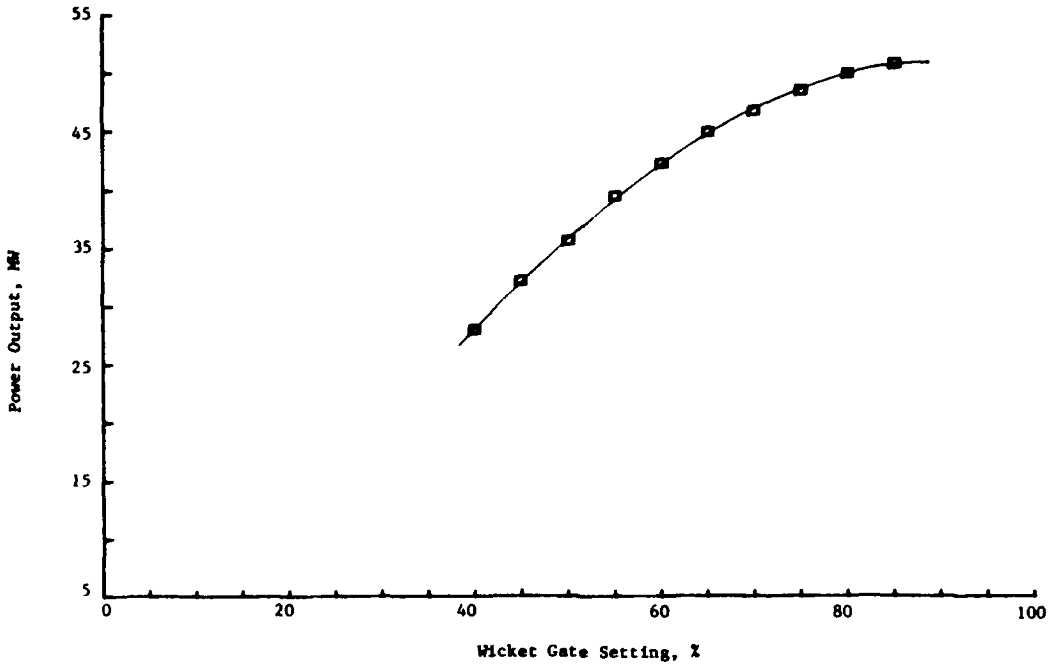


Figure B11. Discharge output versus wicket gate, power output adjusted to 146-ft gross head, Unit 4, vacuum breaker open

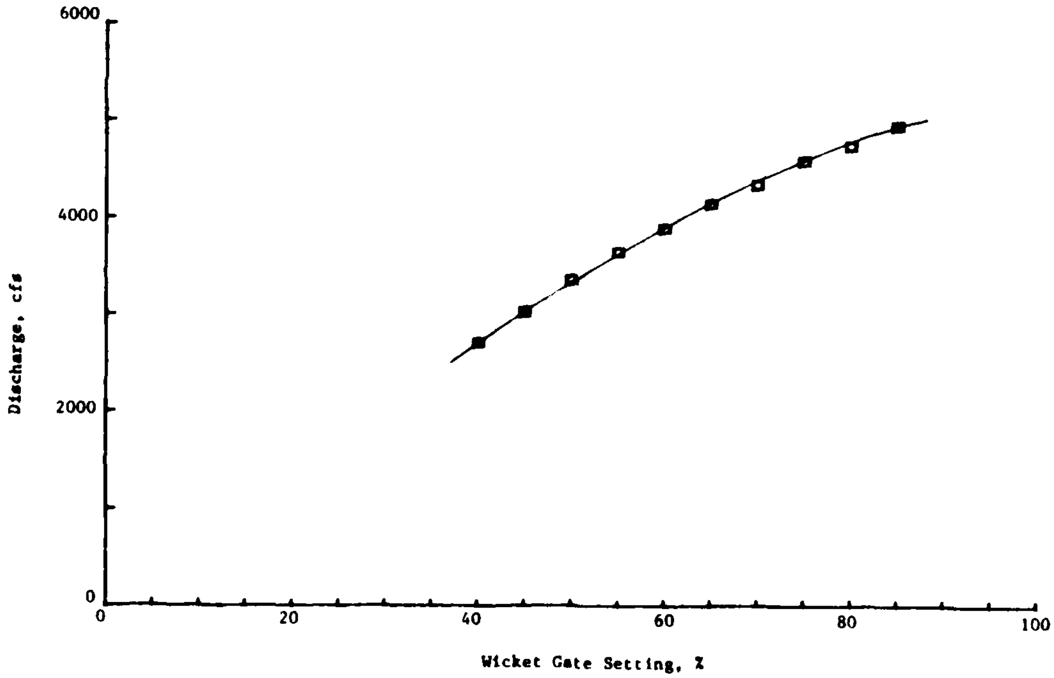


Figure B12. Discharge versus wicket gate, discharge adjusted to 146-ft gross head, Unit 4, vacuum breaker open

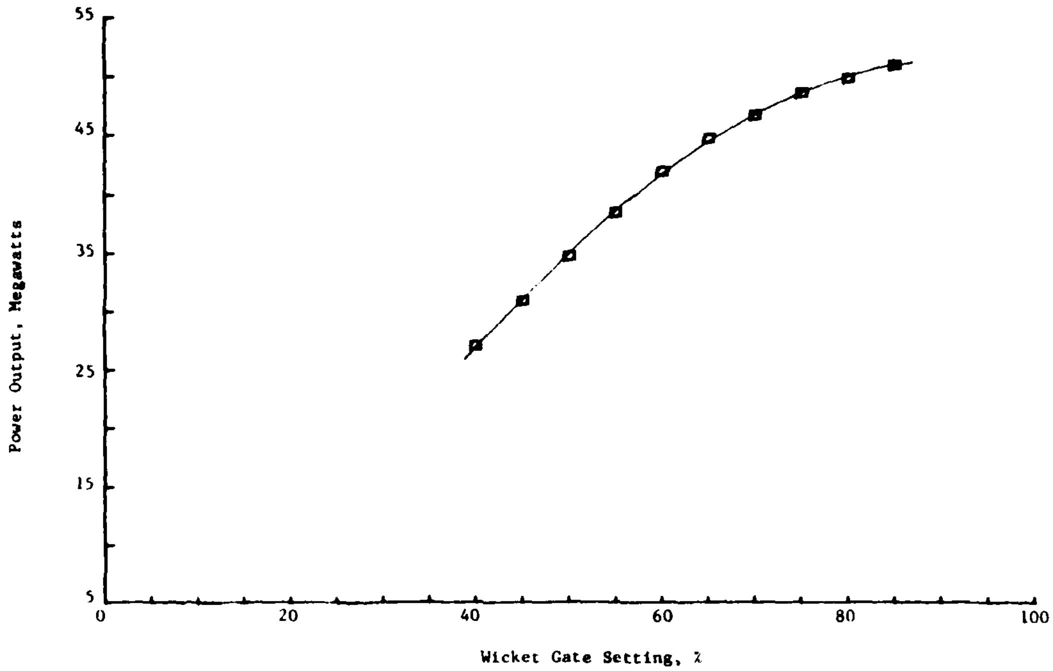


Figure B13. Power versus wicket gate, power output adjusted to 146-ft gross head, Unit 4, bell-mouth intake air supply

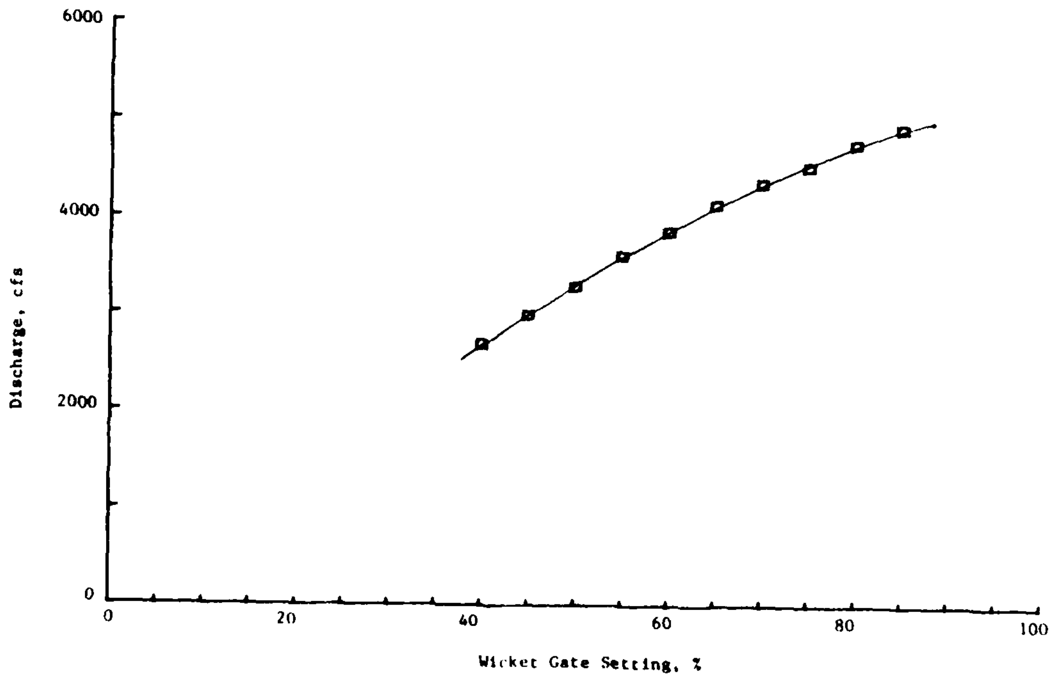


Figure B14. Discharge versus wicket gate, discharge adusted to 146-ft gross head, Unit 4, bell-mouth air supply

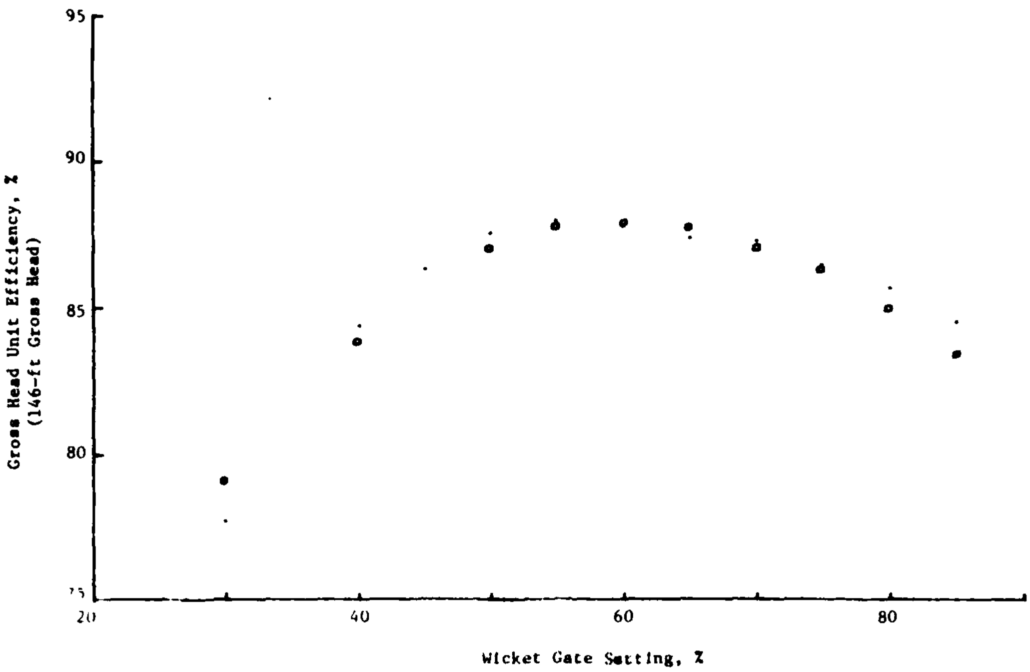


Figure B15. Efficiency versus wicket gate, Unit 2, . = no air flow, o = vacuum breaker open

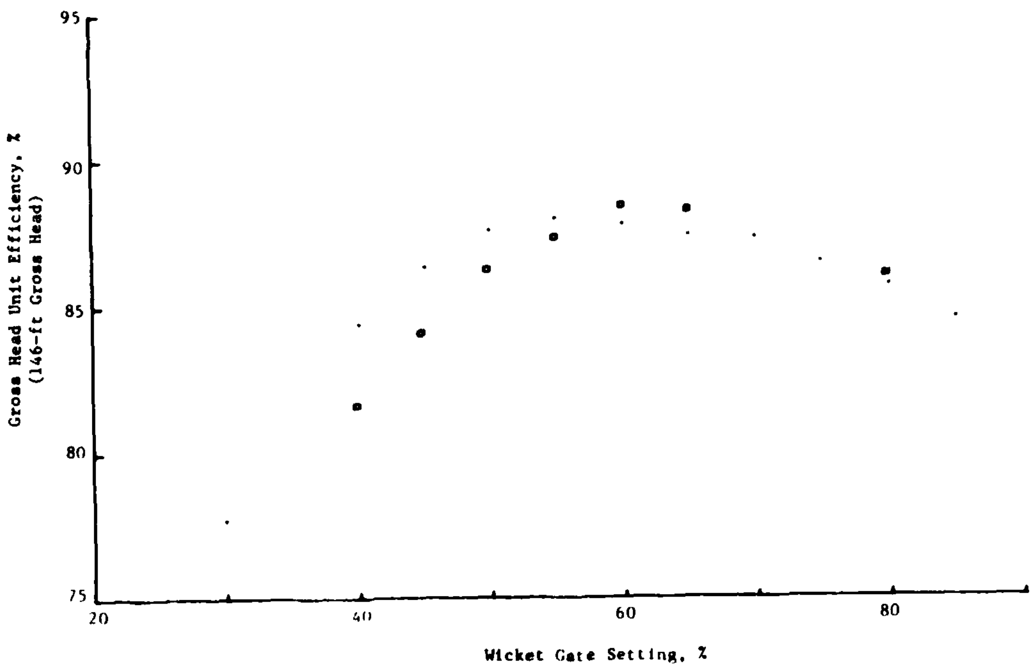


Figure B16. Efficiency versus wicket gate, Unit 2, . = no air flow, o = bell-mouth intake air supply

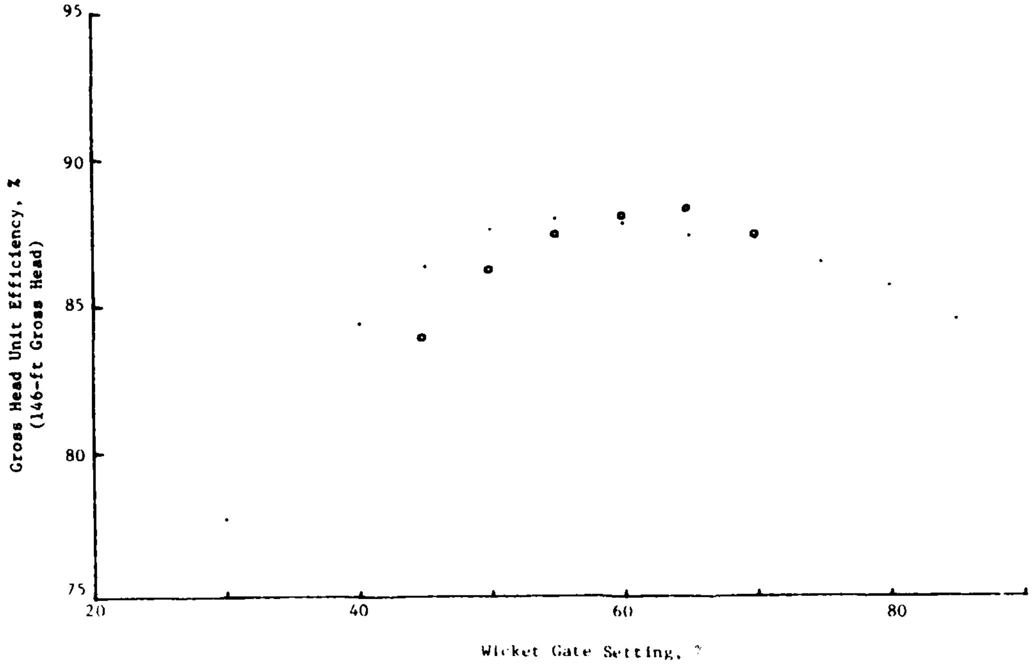


Figure B17. Efficiency versus wicket gate, Unit 2,
. = no air flow, o = blower-supplied air

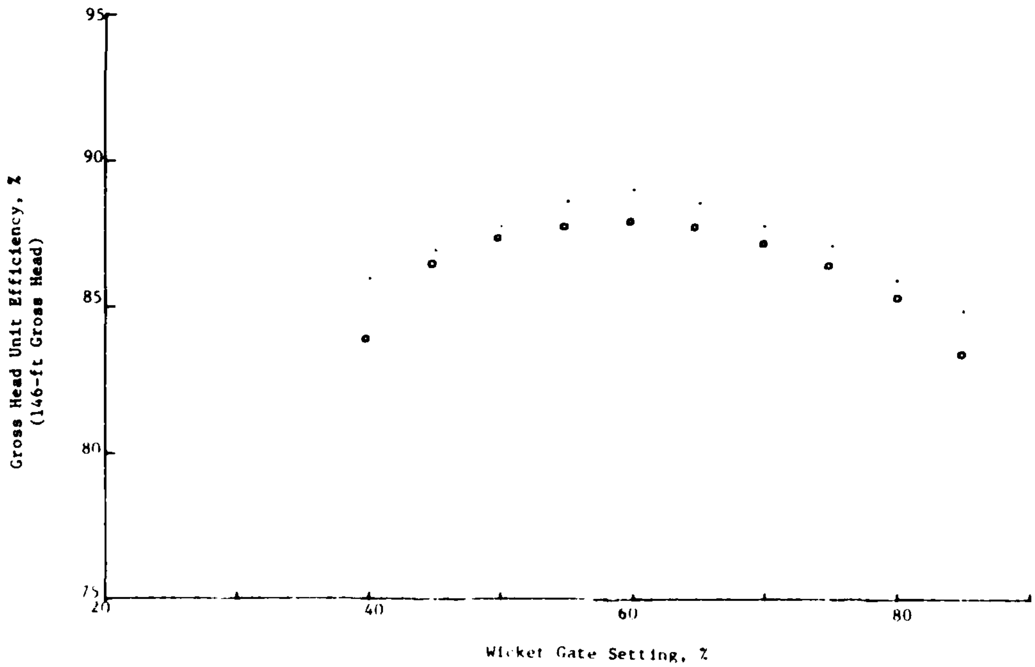


Figure B18. Efficiency versus wicket gate, Unit 4,
. = no air flow, o = vacuum breaker open

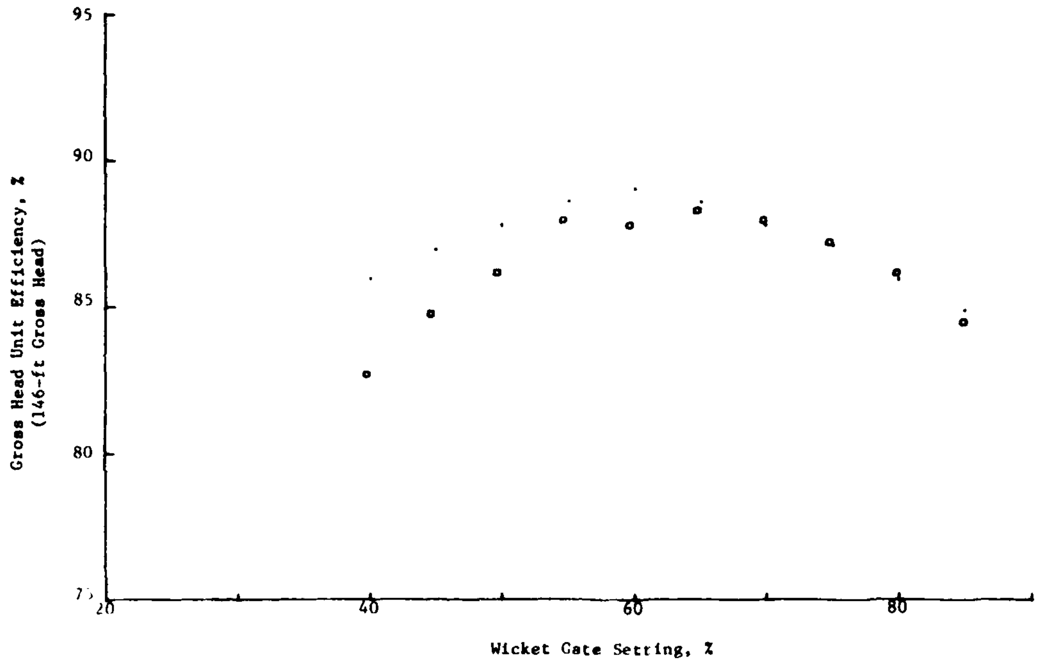


Figure B19. Efficiency versus wicket gate, Unit 4,
. = no air flow, o = bell-mouth intake air supply

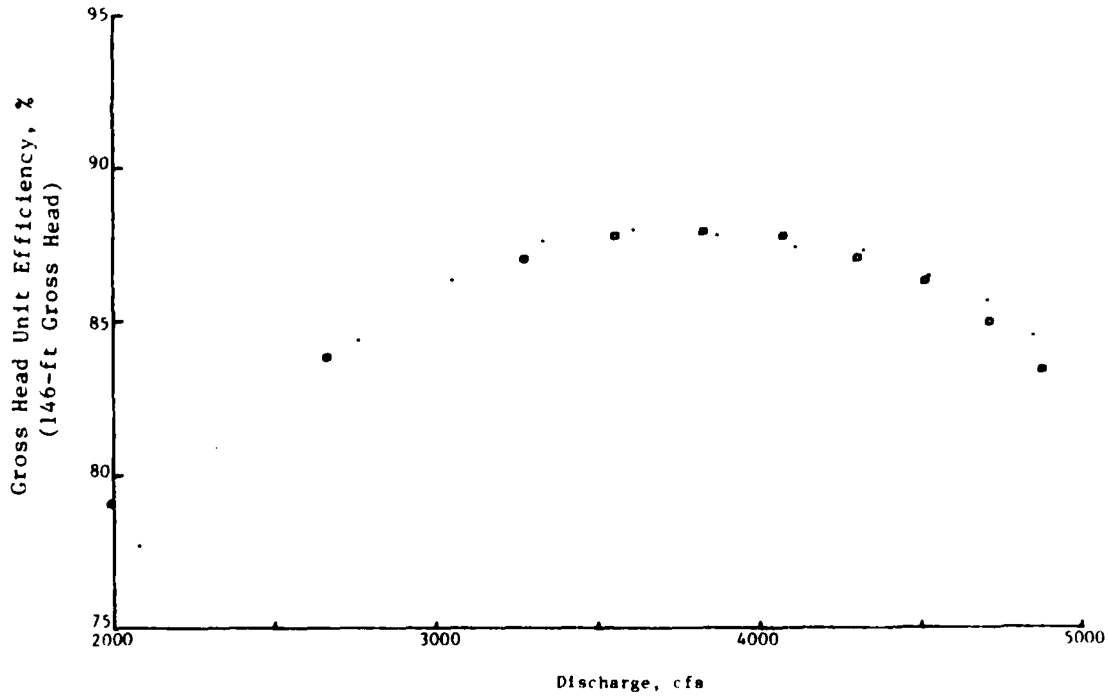


Figure B20. Discharge versus efficiency, Unit 2,
. = no air flow, o = vacuum breaker open

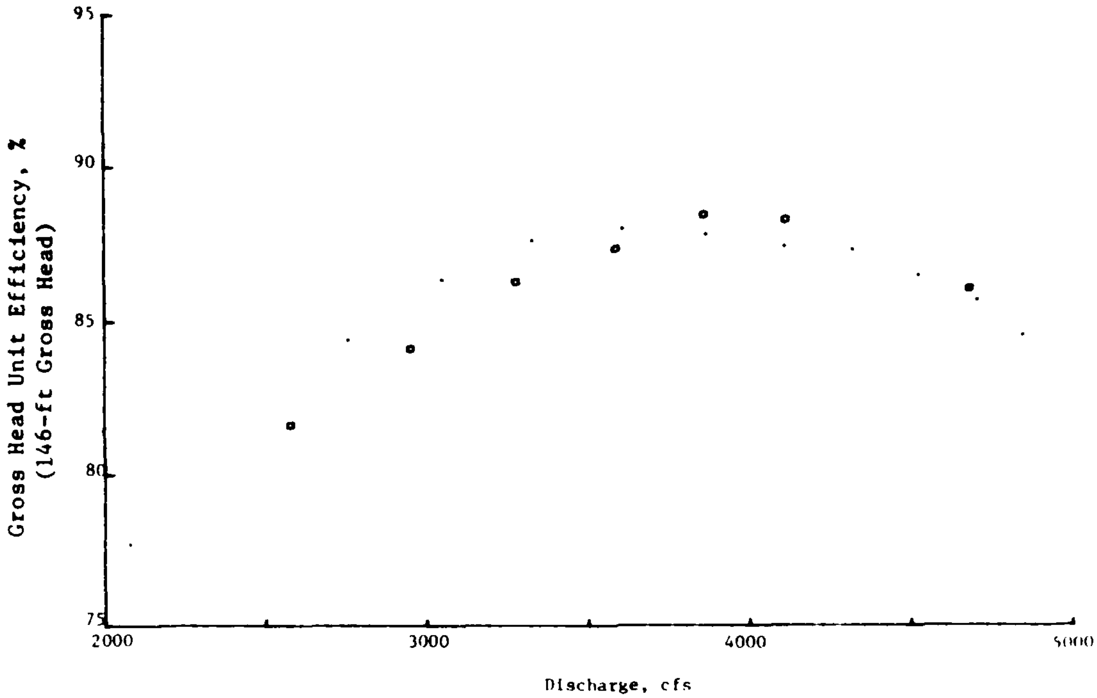


Figure B21. Discharge versus efficiency, Unit 2,
. = no air flow, o = bell-mouth intake air supply

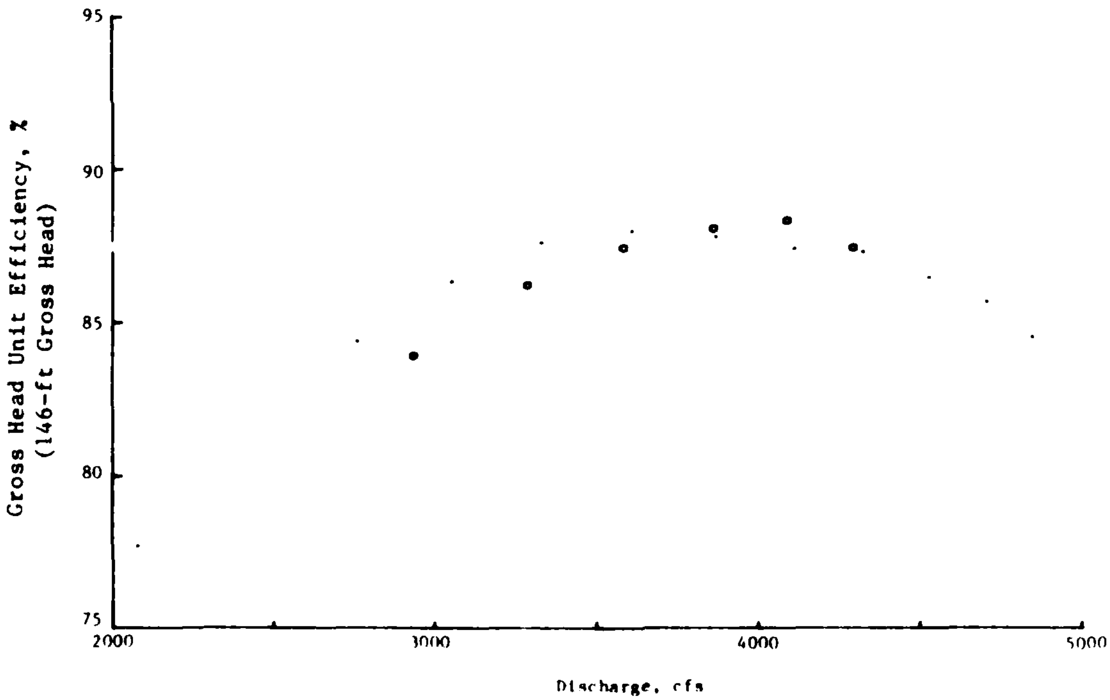


Figure B22. Discharge versus efficiency, Unit 2,
. = no air flow, o = blower-supplied air

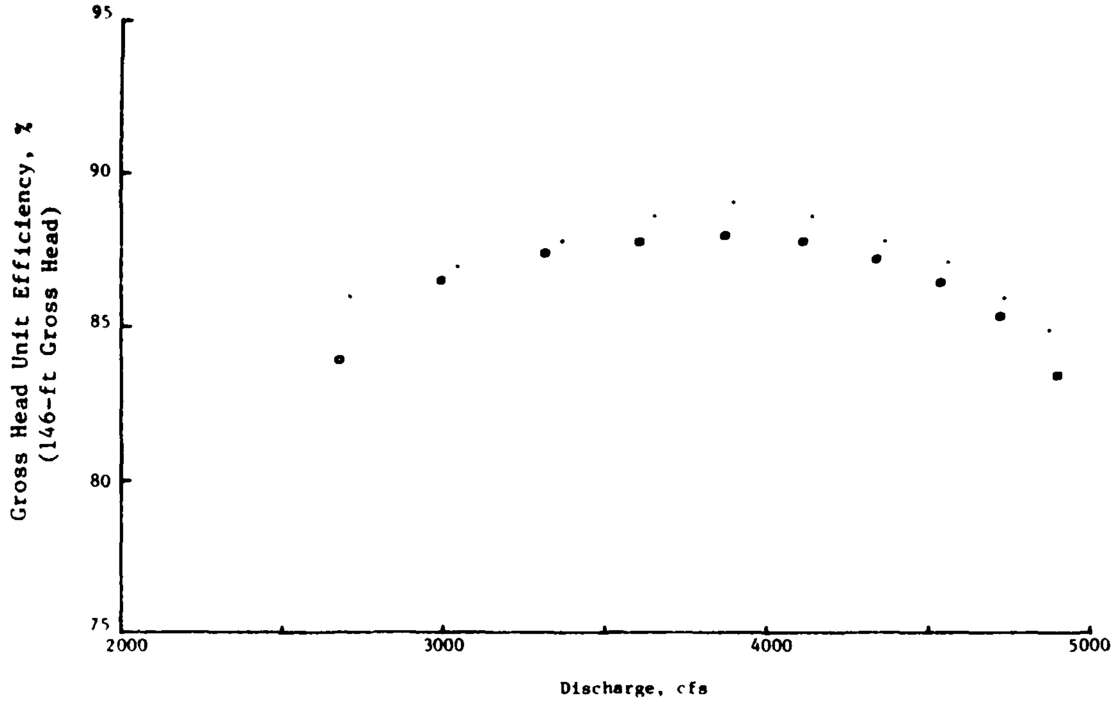


Figure B23. Discharge versus efficiency, Unit 4,
. = no air flow, o = vacuum breaker open

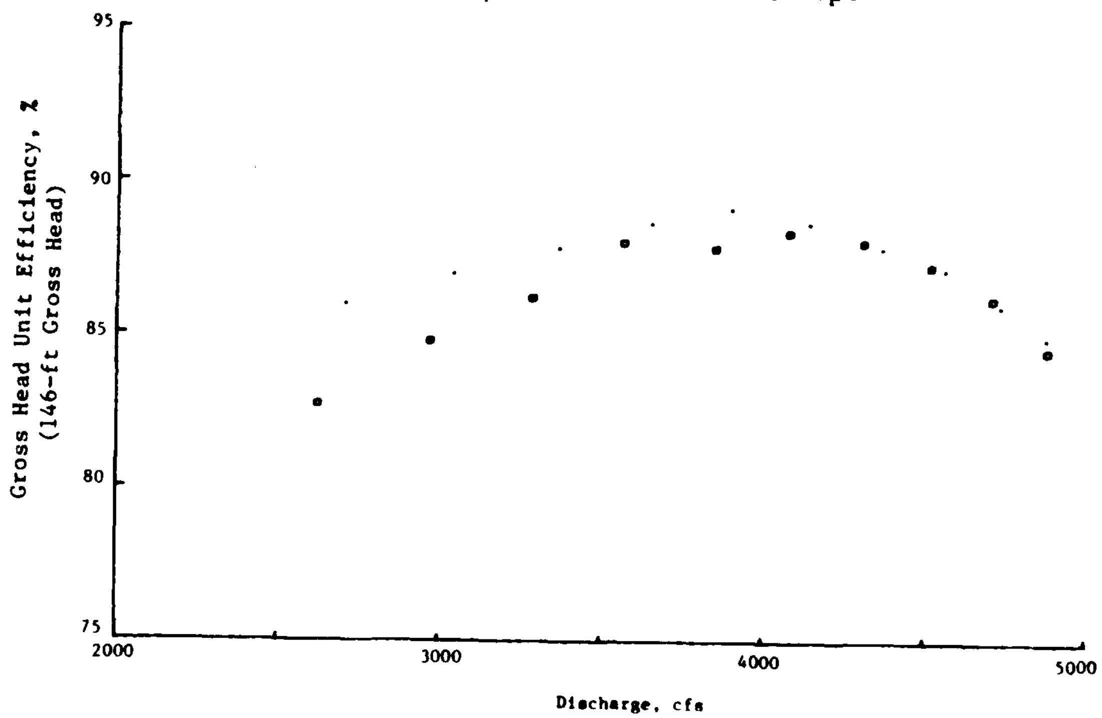


Figure B24. Discharge versus efficiency, Unit 4,
. = no air flow, o = bell-mouth intake air supply

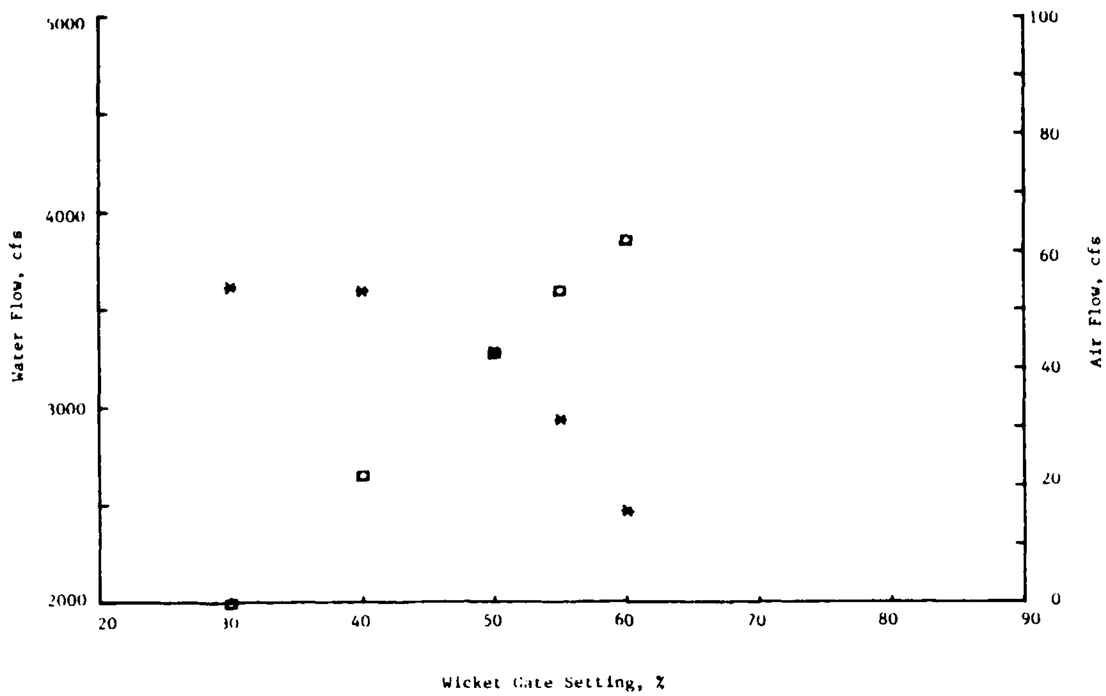


Figure B25. Water flow and air flow versus wicket gate setting, Unit 2, vacuum breaker open, * = air flow, o = water flow

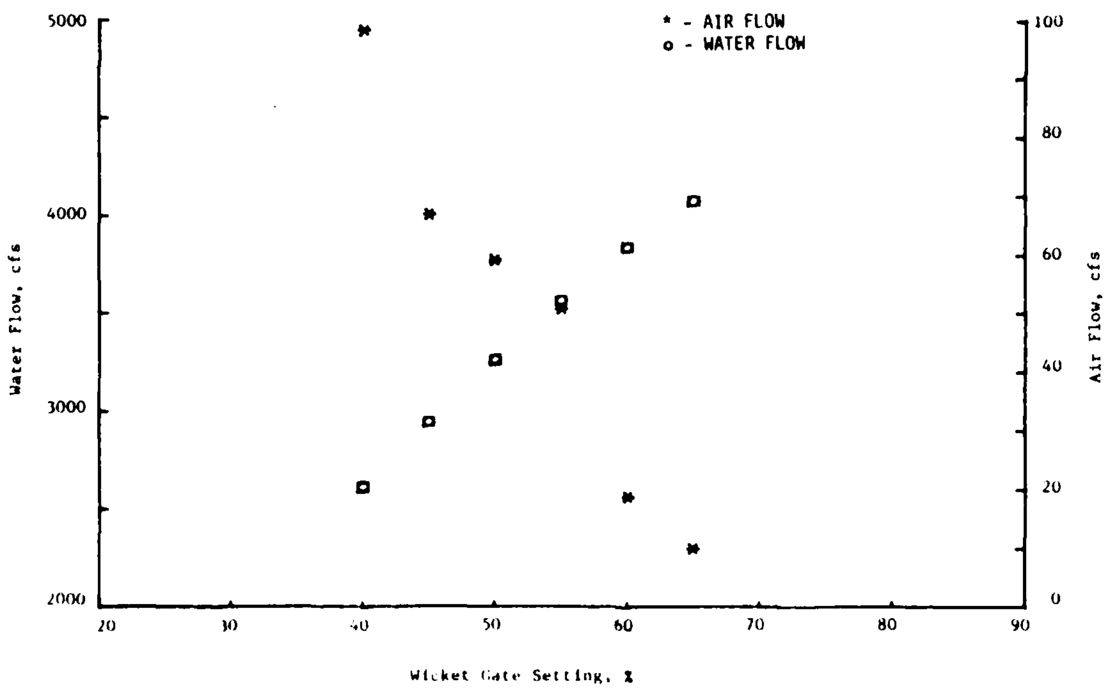


Figure B26. Water flow and air flow versus wicket gate setting, Unit 2, bell-mouth intake air supply

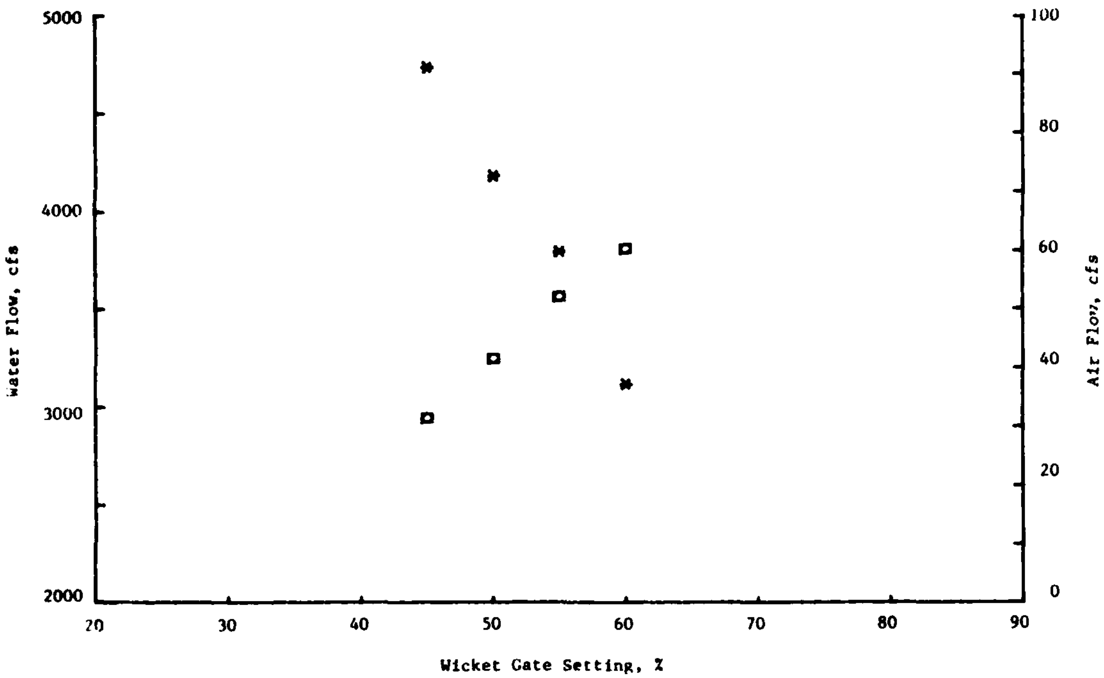


Figure B27. Water flow and air flow versus wicket gate setting, Unit 2, blower-supplied air, * = air flow, o = water flow

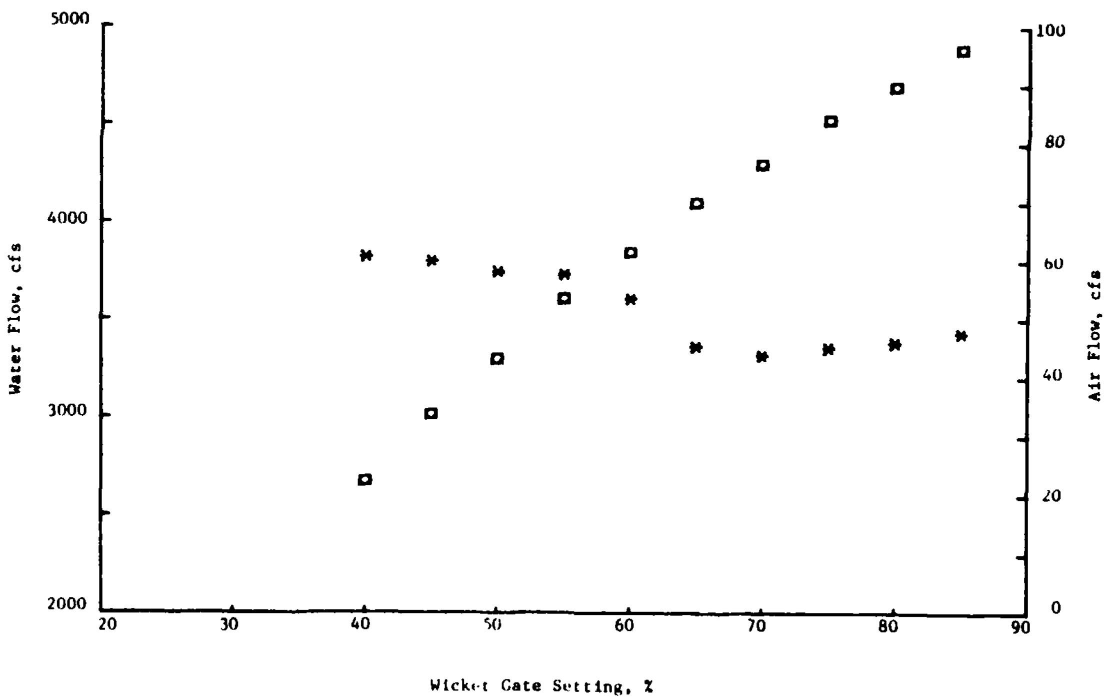


Figure B28. Water flow and air flow versus wicket gate setting, Unit 4, vacuum breaker open, * = air flow, o = water flow

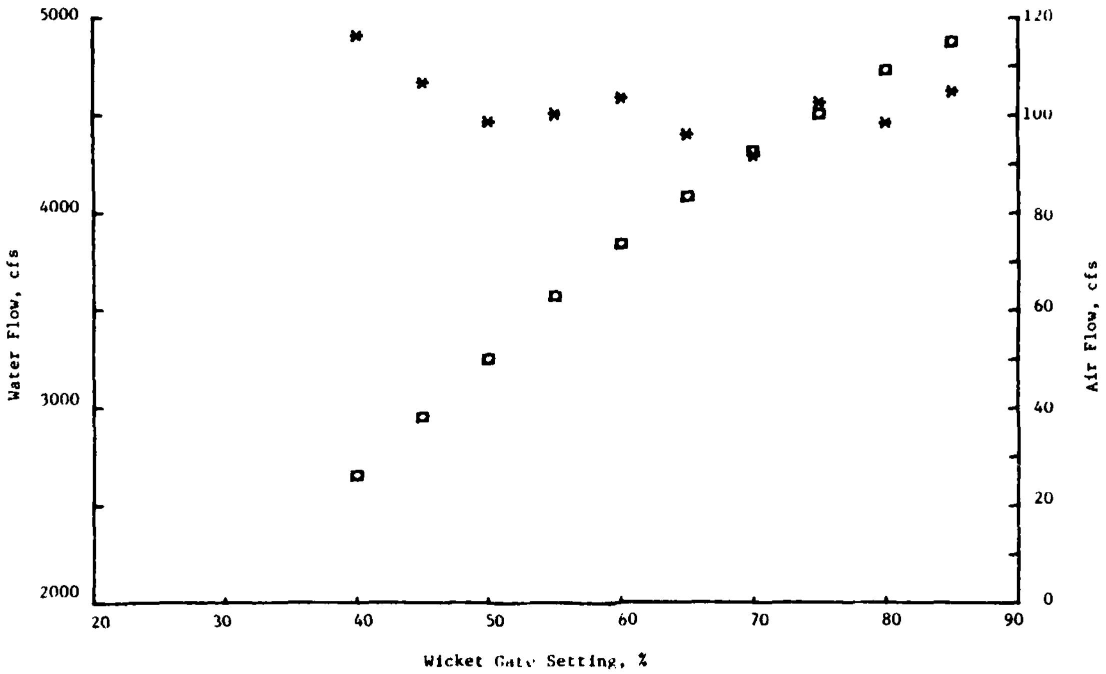


Figure B29. Water flow and air flow versus wicket gate setting, Unit 4, bell-mouth intake air supply, * = air flow, o = water flow

APPENDIX C: TURBINE AERATION COMPUTER MODEL VENTING

```
      PROGRAM TURAER(INPUT,OUTPUT,TAPE5,TAPE6=OUTPUT)
*
*     APRIL 1983   WES-HS3
*     PURPOSE:
*     PREDICTION OF THE DISSOLVED OXYGEN  UPTAKE OF
*     DRAFT TUBE HYDROELECRTRIC TURBINE AERATION SYSTEMS.
******************************************************************
*
*
*******INPUT.
*
*     QAIR - AIR FLOW RATE (FT3/SEC)
*     QWATER - WATER FLOW (TURBINE DISCHARGE)  RATE (FT3/SEC)
*     TEMP - OUTFLOW WATER TEMPERATURE (DEG C)
*     DOICON - INITIAL (UPTAKE) DISSOLVED OXYGEN CONCENTRATION (PPM)
*     ELCL -  CENTERLINE ELEVATION OF DRAFT TUBE OUTLET
*     BETA - ENERGY DISSIPATION COEFFICIENT FOR TURBULENCE
*     ALPHA - GAS TRANSFER RATE COEFFICIENT FOR VENTING
*     AREA - AREA OF DRAFT TUBE OUTLET
*     NTEST - TEST NUMBER
*     QBASE - FLOWRATE FOR WHICH TIME-PRESSURE HISTORY
*               WAS DEVELOPED.
*     NPOINTS - NUMBER OF TIME-HISTORY POINTS (PAIRS)
*     ELTW - TAILWATER ELEVATION (FT)
*     FLOTIME - AIR-WATER CONTACT TIME (SEC)
*     DELT - TIME STEP USED IN SUMMATION OVER THE TOTAL
*             AIR-WATER CONTACT TIME (SEC)
*     PRESSTM - TIME HISTORY,IE, DRAFT TUBE PRESSURE(PSI) VERSES
*                TIME(SEC)
*     DOSCON - SATURATED DISSOLVED OXYGEN CONCENTRATION (PPM)
*
**************************************************************
*
******OUTPUT.
*
*     DOFCON - FINAL (RELEASE) DISSOLVED OXYGEN- PREDICTED-
*       CONCENTRATION (PPM)
*
*****************************************************************
*
********PARAMETERS.
*
      PARAMETER (NSTEP = 1000, NPRESS = 10)
*
*     NSTEP - NUMBER OF PRESSURE POINTS OVER THE
*              TOTAL AIR-WATER CONTACT TIME.
*     NPRESS - NUMBER OF PAIRS OF INPUT PRESSURE-TIME
*               POINTS.
**************************************************************
*
      COMMON /CONTROL/  PRESS(NSTEP), PRESSTM(NPRESS,2)
*
```

```
      COMMON / AA / IFILE, OFILE, END, NPOINTS, NTEST, QBASE
      COMMON / BB / ALPHA, RATIO, QAIR, QWATER, DELT, FLOTIME, PATM
      COMMON / CC / ELCL, ELTW, DOICON, DOFCON, TEMP
      COMMBN / DD / QFIRST, QDEBUG, QERROR, QSTOP, QECHO, QCHECK
      COMMON / EE / AREA, BETA
      INTEGER OFILE,END
      LOGICAL QDEBUG, QFIRST, QSTOP, QERROR, QECHO, QCHECK
*
****** SET UP PROGRAM CONTROL VARIABLES ******
*
      IFILE = 5
      OFILE = 6
      QFIRST = .TRUE.
      QDEBUG = .FALSE.
      QSTOP = .FALSE.
      QERROR = .FALSE.
      QECHO = .FALSE.
      QCHECK = .TRUE.
*
*****************************************************
******* READ INPUT FROM DATA FILE
*
 50   CALL TREAD
*
      IF (QERROR) STOP
*
      CALL HISTORY
*
      CALL AERATE
*
      CALL FINALC
*
***CYCLE BACK TO READ ADDITIANAL DATA SETS
*
      WRITE ( OFILE, 200 )
      GO TO 50
*
 200  FORMAT ( 1H  )
      END
*
```

```
      SUBROUTINE TREAD
*
*  READ THE INPUT DATA FOR TURBINE AERATION SYSTEM
*
      PARAMETER ( NSTEP = 1000, NPRESS = 10 )
      IMPLICIT INTEGER (X)
*
      COMMON / CONTROL / PRESS(NSTEP), PRESSTM(NPRESS,2)
      COMMON / AA / IFILE, OFILE, END, NPOINTS, NTEST, QBASE
      COMMON / BB / ALPHA, RATIO, QAIR, QWATER, DELT, FLOTIME, PATM
      COMMON / CC / ELCL, ELTW, DOICON, DOFCON, TEMP
      COMMON / DD / QFIRST, QDEBUG, QERROR, QSTOP, QECHO, QCHECK
      COMMON / EE / AREA, BETA
      DIMENSION TITLE (7), DUMMY (20)
      INTEGER OFILE,END,DUMMY,CHECK,CHECK1,TITLE
      LOGICAL QFIRST,QDEBUG,QSTOP,QERROR,QECHO, QCHECK
*
      DATA   XENGL, XFILE /4HENGL, 4HFILE /
      DATA   XSTOP, XDEBUG /4HSTOP, 4HDEBU /
      DATA   XDATA, XPRIN  / 4HDATA, 4HPRIN /
      DATA   XMETR, XUNITS / 4HMETR, 4HUNIT /
      DATA   XDELT, XINTER / 4HDELT, 4HINTE /
      DATA   XBLANK, XALPHA / 4HBLAN, 4HALPH /
      DATA   XTIME, XTEMP / 4HTIME, 4HTEMP /
      DATA   XWATER, XBASE / 4HWATE, 4HBASE /
      DATA   XQAIR , XPRESS / 4HAIR , 4HPRES /
      DATA   XTAIL, XELCL / 4HTAIL, 4HCENT /
      DATA   XBETA, XAREA / 4HBETA, 4HAREA /
      DATA   XDOI / 4HDO I /
*************************************************************
*  ADDITIONAL DATA SETS IF QFIRST IS .FALSE.
*
      IF (QSTOP) STOP
      IF ( .NOT. QFIRST ) GO TO 1000
*
*  READ TITLE AND FILE AND CONTROL DATA
*
      READ (IFILE, 505) TITLE
      READ (IFILE, 510) CHECK, IFILE, OFILE
      READ (IFILE, 505) CHECK
      IF (CHECK .EQ. XDEBUG) QDEBUG = .TRUE.
      READ (IFILE, 505) CHECK1
      IF (CHECK1 .NE. XENGL .AND. CHECK1 .NE. XMETR)
     *     CALL ERROR (CHECK, XUNITS)
*
*   ECHO PRINT
*
      READ ( IFILE, 505 ) CHECK
      QECHO = CHECK .EQ. XPRIN
      IF ( .NOT. QECHO ) GO TO 140
      QECHO = .FALSE.
      REWIND IFILE
```

```
      LINE = 1000
      WRITE ( OFILE, 600 )
100   CONTINUE
      READ ( IFILE, 505, END = 110 ) DUMMY
      WRITE ( OFILE, 610 ) LINE, DUMMY
      LINE = LINE +10
      GO TO 100
110   CONTINUE
      REWIND IFILE
      DO 130 I = 1, 5
      READ ( IFILE, 505 ) DUMMY
130   CONTINUE
140   CONTINUE
*
* SET ATMOSPHERIC PRESSURE (UNITS)
*
      PATM = 1.03323
      IF (CHECK1 .EQ. XENGL) PATM = 14.6959
*
      READ (IFILE, 525) CHECK, ELCL
      IF (CHECK .NE. XELCL) CALL ERROR (CHECK, XELCL)
      READ ( IFILE, 525 ) CHECK, AREA
      IF ( CHECK .NE. XAREA ) CALL ERROR ( CHECK, XAREA )
      READ (IFILE, 520) CHECK, DELT
      IF (CHECK .NE. XINTER) CALL ERROR (CHECK, XINTER)
      READ (IFILE, 525) CHECK, FLOTIME
      IF (CHECK .NE. XBASE) CALL ERROR (CHECK, XBASE)
      READ (IFILE, 525) CHECK, ALPHA
      IF (CHECK .NE. XALPHA) CALL ERROR (CHECK, XALPHA)
      READ ( IFILE, 525 ) CHECK, BETA
      IF ( CHECK .NE. XBETA ) CALL ERROR ( CHECK, XBETA )
      READ (IFILE, 505) CHECK
*
*  PARAMETER CHECK
*
      TSTEP = FLOTIME/DELT
      IF (TSTEP .LT. NSTEP) GO TO 105
      WRITE ( OFILE, 530 ) TSTEP
      STOP
105   CONTINUE
*
*  READ THE NUMBER OF DATA POINTS
*  IN PRESSURE-TIME HISTORY
*
      IF (CHECK .NE. XPRESS) CALL ERROR (CHECK, XPRESS)
      READ (IFILE, 515) CHECK, NPOINTS
      IF (CHECK .NE. XTIME) CALL ERROR (CHECK, XTIME)
      NPOINTS = NPOINTS + 1
*
*  PARAMETER CHECK
*
      IF (NPOINTS .LE. NPRESS) GO TO 33
      WRITE ( OFILE, 540 ) NPOINTS
```

```
            STOP
     33     CONTINUE
*
*  READ THE PRESSURE-TIME HISTORY
*
            DO 20 I=1,NPOINTS - 1
            READ (IFILE,550) PRESSTM(I,1),PRESSTM(I,2)
     20     CONTINUE
*
            READ ( IFILE, 525 ) CHECK, QBASE
            IF ( CHECK .NE. XBASE ) CALL ERROR ( CHECK, XBASE )
*
*  BEGIN DATA THAT CAN BE CHANGED
*  TO REPRESENT ADDITIONAL DATA SETS.
*  ALL OF THE INPUT DATA ABOVE IS
*  UNCHANGED FROM ONE DATA
*  SET TO ANOTHER.
*
   1000     CONTINUE
            READ (IFILE, 560) TITLE, NTEST
            READ (IFILE, 525) CHECK, ELTW
            IF (CHECK .NE. XTAIL) CALL ERROR (CHECK, XTAIL)
            READ (IFILE, 525) CHECK, TEMP
            IF (CHECK .NE. XTEMP) CALL ERROR (CHECK, XTEMP)
            READ (IFILE, 520) CHECK, QAIR
            IF (CHECK .NE. XQAIR) CALL ERROR (CHECK, XQAIR)
            READ ( IFILE, 520 ) CHECK, QWATER
            IF ( CHECK .NE. XWATER ) CALL ERROR ( CHECK, XWATER )
            READ (IFILE, 520) CHECK, DOICON
            IF (CHECK .NE. XDOI) CALL ERROR (CHECK, XDOI)
            READ (IFILE, 520) CHECK
            IF (CHECK .NE. XDATA) GO TO 60
            BACKSPACE IFILE
            QFIRST = .FALSE.
            RETURN
     60     CONTINUE
            IF (CHECK .EQ. XSTOP) QSTOP = .TRUE.
            IF (CHECK .NE. XSTOP) CALL ERROR (CHECK, XSTOP)
            RETURN
    505     FORMAT ( 20A4 )
    510     FORMAT ( A4, 6X, 2I5 )
    515     FORMAT ( A4, 16X, I5  )
    520     FORMAT ( A4, 6X,  F10.2 )
    525     FORMAT ( A4, 21X, F10.2 )
    530     FORMAT (    ', 'PARAMETER NSTEP IS TOO SMALL',/,
         *             'SHOULD BE ', I4, '  RECOMPLILE' )
    540     FORMAT (' ', 'PARAMETER NPRESS IS TOO SMALL ',/,
         *             'SHOULD BE ', I5 )
    550     FORMAT(2F10.2)
    560     FORMAT ( 7A4, A7 )
    600     FORMAT ( 1H1 )
    610     FORMAT ( 10X, I6, 7X, 3H***, 20A4 )
*
```

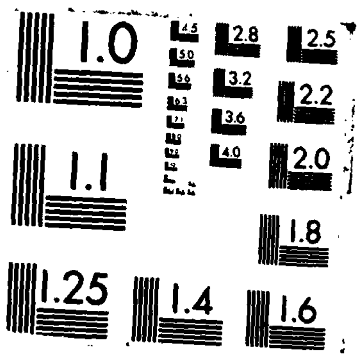
```
1250          END
1251*
```

```
      SUBROUTINE HISTORY
*
* COMPUTES THE PRESSURE HISTORY OVER THE TOTAL AIR-WATER
* CONTACT TIME AT EACH TIME STEP(DELT).
*
      PARAMETER (NSTEP = 1000, NPRESS = 10)
*
      COMMON /CONTROL/  PRESS(NSTEP), PRESSTM(NPRESS,2)
*
      COMMON / AA / IFILE, OFILE, END, NPOINTS, NTEST, QBASE
      COMMON / BB / ALPHA, RATIO, QAIR, QWATER, DELT, FLOTIME, PATM
      COMMON / CC / ELCL, ELTW, DOICON, DOFCON, TEMP
      COMMON / DD / QFIRST, QDEBUG, QERROR, QSTOP, QECHO
      COMMON / EE / AREA, BETA
*
      LOGICAL QDEBUG
*
      DIMENSION ARRAY ( NPRESS )
      INTEGER START,END,OFILE
*
* LOOP OVER EACH INPUT PRESSURE-TIME POINT IN 'ARRAY'
* AND GENERATE PRESSURE POINTS FOR EACH TIME STEP(DELT).
*
*
* SCALE THE INPUT TIME POINTS BASED
* UPON THE RATIO QBASE/QWATER
*
      NPM1 = NPOINTS - 1
*
      SCALE = QBASE /QWATER
*
      DO 10 I = 1, NPM1
      ARRAY ( I ) = PRESSTM (I,1) * SCALE
 10   CONTINUE
*
*  SET LAST TIME-HISTORY POINT TO ATMOSPHERIC USING
*  RISE VELOCITY OF BUBBLES  TO BE 2.0 FT/SEC.
*
      VRISE = 2.0
      ARRAY ( NPOINTS ) = ARRAY (NPM1) + ( ELTW-ELCL )/VRISE
      PRESSTM ( NPOINTS, 2 ) = PATM
*
      IF ( QDEBUG ) WRITE ( OFILE,500 ) ( ARRAY(I),I=1,NPOINTS )
      IF ( QDEBUG ) WRITE ( OFILE,505 ) ( PRESSTM(I,2),I=1,NPOINTS
*
      LOOP = 1
      PRESS(1) = PRESSTM(1,2)
*
      DO 99 K=1,NPM1
*
* FIND THE NUMBER OF TIME STEPS BETWEEN TWO INPUT
* TIME-HISTORY POINTS
```

```
*
        JUMP = NINT  ( ( ARRAY(K+1) - ARRAY(K)) / DELT )
*
*  FIND THE PRESSURE INCREMENT
*
        BUMP = ( PRESSTM(K+1,2) - PRESSTM(K,2)) / FLOAT(JUMP)
        IF ( QDEBUG ) WRITE ( OFILE,510 ) JUMP, BUMP
*
*  FILL IN THE COMPLETE PRESSURE ARRAY
*
        START = LOOP +1
        END = LOOP + JUMP
*
        IF (END .LE. NSTEP) GO TO 55
*
        WRITE ( OFILE, 600 )
 600    FORMAT ( '  NSTEP IS TOO SMALL - RECOMPILE' )
        STOP
**
*
 55     DO 80 J=START,END
        PRESS(J) = PRESS(J-1) + BUMP
 80     CONTINUE
*
        LOOP = LOOP + JUMP
        IF ( QDEBUG ) WRITE ( OFILE,520 ) START, END,
     *      ( PRESS(J), J = START, END )
*
 99     CONTINUE
 500    FORMAT ( 23H$$ SCALED TIME ARRAY $$,//, 10F8.2 )
 505    FORMAT ( 27H$$ SCALED PRESSURE ARRAY $$,//, 10F8.2 )
 510    FORMAT ( 8HJUMP =  ,I4,3X,8HBUMP =  ,F8.2 )
 520    FORMAT ( 21HPRESSURE HISTORY FROM,I4,2HTO,I4,/,( 10F8.2) )
*
        RETURN
        END
*
```

AD-A181 372 ENVIRONMENTAL & WATER QUALITY OPERATIONAL STUDIES: IMPROVEMENT OF HYDROPO (U) ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MS ENVIR 2/2

UNCLASSIFIED S C WILHELMS ET AL MAR 87 WES/TR/E-87-3 F/G 10/2 NL


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0

```
      SUBROUTINE AERATE
*
*  COMPUTES THE  DISSOLVED OXYGEN UPTAKE OF
*        TURBINE REAERATION SYSTEMS.
*
*       JUNE 1982 - WES-HS3
*
      PARAMETER (NSTEP = 1000, NPRESS = 10)
      COMMON /CONTROL/  PRESS(NSTEP), PRESSTM(NPRESS,2)
*
      COMMON / AA / IFILE, OFILE, END, NPOINTS, NTEST, QBASE
      COMMON / BB / ALPHA, RATIO, QAIR, QWATER, DELT, FLOTIME, PATM
      COMMON / CC / ELCL, ELTW, DOICON, DOFCON, TEMP
      COMMON / DD / QFIRST, QDEBUG, QERROR, QSTOP, QECHO
      COMMON / EE / AREA, BETA
*
      INTEGER END,OFILE
      LOGICAL QDEBUG
*
      RATIO = QAIR / QWATER
*
* CALCULATE THE SATURATION CONCENTRATION
*
      DOSCON = 1.0 / ( 0.00209 * TEMP + 0.06719 )
*
* AIR ASPIRATION/INJECTION MODEL PER TIME STEP
*
      CONSTO = ( ALPHA ) * (1.024 ** (TEMP-20.)) * RATIO * DELT
*
* CALCULATE PENSTOCK DEFICIT
*
      CSO2 = DOSCON * PRESS(1) / PATM
      DI = CSO2 - DOICON
*
* ITERATE THROUGH PRESSURE HISTORY
*
      IF (QDEBUG) WRITE(OFILE,200)
      K = END - 1
      DO 100 I = 1, K
*
* CALCULATE NEW DEFICIT
*
      DF = DI * EXP(-CONSTO)
*
* ADJUST DEFICIT FOR HYDROSTATIC PRESSURE
*
      DOFCON = DOSCON * PRESS(I) / PATM - DF
*
      DI = DOSCON * PRESS(I+1) / PATM - DOFCON
*
      BB = DOSCON *PRESS(I+1) / PATM
      IF ( QDEBUG ) WRITE (OFILE,50) DI, BB, DOFCON, DF
```

```
*
 100      CONTINUE
*
*  CALCULATE VELOCITY HEAD AT DRAFT TUBE OUTLET
*
          DELENG = ( QWATER / AREA ) ** 2.0 / 64.348
*
*  CALCULATE DEFICIT AFTER TURBULENT REAERATION
*
          DF = DI * EXP ( -BETA*(1.024**(TEMP -20.))*DELENG)
*
*  CALCULATE RELEASE DO
*
          DOFCON = DOSCON - DF
*
          RETURN
*
 200      FORMAT(' ','$$',4X,'DI',7X,'DOS',7X,'DOF',5X,'DF')
  50      FORMAT(4(F8.3,2X))
          END
*
```

```
            SUBROUTINE FINALC
*
*  OUTPUT FOR SUBROUTINE AERATE
*
*
            COMMON / AA / IFILE, OFILE, END, NPOINTS, NTEST, QBASE
            COMMON / BB / ALPHA, RATIO, QAIR, QWATER, DELT, FLOTIME, PATM
            COMMON / CC / ELCL, ELTW, DOICON, DOFCON, TEMP
            COMMON / DD / QFIRST, QDEBUG, QERROR, QSTOP, QECHO, QCHECK
*
            INTEGER OFILE,END
            LOGICAL QFIRST, QCHECK
            IF ( QCHECK ) WRITE ( OFILE, 600 )
            IF ( QCHECK ) WRITE ( OFILE, 610 )
            IF ( QCHECK ) WRITE ( OFILE, 620 )
            IF ( QCHECK ) WRITE ( OFILE, 622 )
            IF ( QCHECK ) WRITE ( OFILE, 625 )
            QCHECK = .FALSE.
            WRITE ( OFILE, 630 ) NTEST,ELTW,TEMP,QWATER,QAIR,DOICON,DOFCON
  600       FORMAT ( 1H1 )
  610       FORMAT ( ///,2X,4HTEST,4X,4HTAIL,5X,11HTEMPERATURE,
       *           4X,5HWATER,4X,3HAIR,4X,7HINITIAL,6X,6HFINAL  )
  620       FORMAT ( 1X,6HNUMBER,3X,5HWATER,19X,4HFLOW,5X,4HFLOW,2X,
       *           9HDISSOLVED,3X,9HDISSOLVED )
  622       FORMAT ( 50X,6HOXYGEN,7X,6HOXYGEN )
  625       FORMAT ( 53X, 14HCONCENTRATIONS )
  630       FORMAT ( A7,2X,F6.2,7X,F5.2,7X,F5.0,4X,F5.1,4X,
       *           F6.2,5X,F6.2 )
           RETURN
           END
*
```

```
      SUBROUTINE ERROR ( CHECK, CHAR )
*
* INPUT DATA FILE ERRORS FOR TURBINE AERATION
* STRUCTURES
*
*
      COMMON / AA / IFILE, OFILE, END, NPOINTS, NTEST, QBASE
      COMMON / DD / QFIRST, QDEBUG, QERROR, QSTOP, QECHO
      INTEGER OFILE, CHECK, CHAR
      LOGICAL QERROR
*
      WRITE (OFILE, 100) CHECK, CHAR
      QERROR = .TRUE.
      RETURN
 100  FORMAT ( ' ' , '*** INPUT DATA ERROR ', ' WAS ', A4,
     *        2X, '**EXPECTING ', A4 ,' **' )
      END
```

APPENDIX D: SAMPLE INPUT TO AND OUTPUT FROM VENTING CODE

```
CLARKS HILL TURBINE AERATION - SEPT 81
FILE          05   06
NO DEBUG             .
ENGLISH
PRINT OUTPUT
CENTERLINE ELEVATION            168.0
AREA OF DRAFT TUBE EXIT         672.0
INTERVAL            0.1
BASE FLOW TIME                   15.0
ALPHA COEFFICIENT                0.33
BETA COEFFICIENT                 0.15
PRESSURE-TIME HISTORY
TIME       PRESSURE       4
       0.0       15.0
       1.4       25.5
       2.8       29.1
       9.0       25.5
BASE FLOWRATE                   3700.
DATASET CLARKS HILL TURBINE TEST 1
TAILWATER ELEVATION             186.4
TEMPERATURE                      18.9
AIR FLOW         49.7
WATER FLOW     5280.
DO INITIAL        2.9
DATASET CLARKS HILL TURBINE TEST 2
TAILWATER ELEVATION             186.4
TEMPERATURE                      18.9
AIR FLOW         47.0
WATER FLOW    5160.0
DO INITIAL        2.9
DATASET CLARKS HILL TURBINE TEST 3
TAILWATER ELEVATION             186.4
TEMPERATURE                      18.9
AIR FLOW         39.7
WATER FLOW    5193.0
DO INITIAL        2.9
DATASET CLARKS HILL TURBINE TEST 4
TAILWATER ELEVATION             186.4
TEMPERATURE                      18.9
AIR FLOW         29.0
WATER FLOW    5190.0
DO INITIAL        2.9
DATASET CLARKS HILL TURBINE TEST 5
TAILWATER ELEVATION             186.4
TEMPERATURE                      18.9
AIR FLOW         20.5
WATER FLOW    5193.0
DO INITIAL        2.9
DATASET CLARKS HILL TURBINE TEST 6
TAILWATER ELEVATION             186.4
TEMPERATURE                      18.9
AIR FLOW         10.3
```

```
WATER FLOW    5193.0
DO INITIAL       2.9
DATASET CLARKS HILL TURBINE TEST 7
TAILWATER ELEVATION           186.6
TEMPERATURE                    18.9
AIR FLOW         0.0
WATER FLOW    5193.0
DO INITIAL       2.9
DATASET CLARKS HILL TURBINE TEST 9
TAILWATER ELEVATION           186.8
TEMPERATURE                    18.4
AIR FLOW        41.0
WATER FLOW    4887.0
DO INITIAL       2.9
DATASET CLARKS HILL TURBINE TEST 10
TAILWATER ELEVATION           186.8
TEMPERATURE                    18.3
AIR FLOW        41.0
WATER FLOW     4530.
DO INITIAL       2.9
DATASET CLARKS HILL TURBINE TEST 13
TAILWATER ELEVATION           186.9
TEMPERATURE                    18.3
AIR FLOW        39.7
WATER FLOW    4144.0
DO INITIAL       2.9
DATASET CLARKS HILL TURBINE TEST 14
TAILWATER ELEVATION           185.1
TEMPERATURE                    18.9
AIR FLOW        58.1
WATER FLOW    3736.0
DO INITIAL       2.9
DATASET CLARKS HILL TURBINE TEST 17
TAILWATER ELEVATION           185.1
TEMPERATURE                    18.9
AIR FLOW        59.7
WATER FLOW    3187.0
DO INITIAL       2.9
DATASET CLARKS HILL TURBINE TEST 18
TAILWATER ELEVATION           185.1
TEMPERATURE                    18.9
AIR FLOW        61.1
WATER FLOW    3511.0
DO INITIAL       2.9
DATASET CLARKS HILL TURBINE TEST 21
TAILWATER ELEVATION           185.2
TEMPERATURE                    19.1
AIR FLOW        53.2
WATER FLOW    3951.0
DO INITIAL       2.9
DATASET CLARKS HILL TURBINE TEST 22
TAILWATER ELEVATION           185.2
TEMPERATURE                    19.0
```

```
AIR FLOW        49.2
WATER FLOW    4378.0
DO INITIAL       2.9
DATASET CLARKS HILL TURBINE TEST 25
TAILWATER ELEVATION              185.2
TEMPERATURE                       19.0
AIR FLOW        50.6
WATER FLOW    4747.0
DO INITIAL       2.9
DATASET CLARKS HILL TURBINE TEST 26
TAILWATER ELEVATION              185.2
TEMPERATURE                       19.0
AIR FLOW        53.4
WATER FLOW    5046.0
DO INITIAL       2.9
DATASET CLARKS HILL TURBINE TEST 30
TAILWATER ELEVATION              185.0
TEMPERATURE                       19.0
AIR FLOW        48.3
WATER FLOW    3420.0
DO INITIAL       2.9
DATASET CLARKS HILL TURBINE TEST 31
TAILWATER ELEVATION              185.0
TEMPERATURE                       19.0
AIR FLOW        39.0
WATER FLOW    3431.0
DO INITIAL       2.9
DATASET CLARKS HILL TURBINE TEST 32
TAILWATER ELEVATION              185.2
TEMPERATURE                       19.0
AIR FLOW        24.2
WATER FLOW    3429.0
DO INITIAL       2.9
DATASET CLARKS HILL TURBINE TEST 33
TAILWATER ELEVATION              185.4
TEMPERATURE                       19.0
AIR FLOW        18.3
WATER FLOW    3437.0
DO INITIAL       2.9
STOP
```

TEST NUMBER	TAIL WATER	TEMPERATURE	WATER FLOW	AIR FLOW	INITIAL DISSOLVED OXYGEN CONCENTRATIONS	FINAL DISSOLVED OXYGEN
TEST 1	186.40	18.90	5280.	49.7	2.90	4.20
TEST 2	186.40	18.90	5160.	47.0	2.90	4.16
TEST 3	186.40	18.90	5193.	39.7	2.90	4.10
TEST 4	186.40	18.90	5190.	29.0	2.90	4.00
TEST 5	186.40	18.90	5193.	20.5	2.90	3.92
TEST 6	186.40	18.90	5193.	10.3	2.90	3.82
TEST 7	186.60	18.90	5193.	0.0	2.90	3.72
TEST 9	186.80	18.40	4887.	41.0	2.90	4.08
TEST 10	186.80	18.30	4530.	41.0	2.90	4.03
TEST 13	186.90	18.30	4144.	39.7	2.90	3.99
TEST 14	185.10	18.90	3736.	58.1	2.90	4.26
TEST 17	185.10	18.90	3187.	59.7	2.90	4.45
TEST 18	185.10	18.90	3511.	61.1	2.90	4.37
TEST 21	185.20	19.10	3951.	53.2	2.90	4.16
TEST 22	185.20	19.00	4378.	49.2	2.90	4.10
TEST 25	185.20	19.00	4747.	50.6	2.90	4.13
TEST 26	185.20	19.00	5046.	53.4	2.90	4.19
TEST 30	185.00	19.00	3420.	48.3	2.90	4.16
TEST 31	185.00	19.00	3431.	39.0	2.90	4.00
TEST 32	185.20	19.00	3429.	24.2	2.90	3.73
TEST 33	185.40	19.00	3437.	18.3	2.90	3.62

END
7-87
DTIC